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THE BELL ISLAND BAY GROUP, REMNANT OF AN EARLY PROTEROZOIC ENSIALIC MARGINAL BASIN IN WOPMAY OROGEN, DISTRICT OF MACKENZIE

Ingrid G. Reichenbach

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THE BELL ISLAND BAY GROUP, REMNANT OF AN EARLY PROTEROZOIC ENSIALIC MARGINAL BASIN IN WOPMAY OROGEN, DISTRICT OF MACKENZIE

Abstract

The 1898 Ma Bell Island Bay Group occurs in the western part of Wopmay Orogen, an early Proterozoic orogenic belt developed on the western margin of the Archean Slave Craton. This 4 km thick group comprises five formations, from oldest to youngest: 1) Beaverlodge Lake Sandstone, subaerially deposited conglomerate and sandstone; 2) Zebulon Formation, subaerially erupted calc-alkaline volcanic rocks ranging from basalt to rhyolite; 3) Conjuror Bay Formation, shallow marine siliciclastics; 4) Bloom Basalt, tholeiitic pillow basalt; and 5) Fishtrap Lake Gabbro, tholeiitic gabbro sills and dykes interpreted to be comagmatic with Bloom Basalt. The Bell Island Bay Group unconformably overlies a sialic basement complex (Hottah Terrane) and is unconformably overlain by volcanic and sedimentary continental arc rocks of the Great Bear Magmatic Zone.

Based on depositional environment, chemistry, regional tectonic setting and comparison with Mesozoic-Recent analogues, rocks of the Beaverlodge Lake Sandstone and the Zebulon Formation are interpreted to constitute part of a continental magmatic arc and the Conjuror Bay Formation, Bloom Basalt and Fishtrap Lake Gabbro represent material related to the formation of a younger marginal basin.

The tholeiitic lavas and intrusions of the Bell Island Bay Group are similar in age, geochemistry and lithology to the Akaitcho and Grant groups, the lowermost stratigraphic units of the internal zone of Wopmay Orogen, suggesting that the three groups are correlative and were deposited within the same basin. If this is correct, then the Wopmay Orogen is better considered to represent magmatism and tectonism related to an evolving Andean-type plate margin, rather than to the Wilson Cycle.

Résumé

Le groupe de Bell Island Bay de 1898 Ma se trouve dans la partie ouest de l'orogène de Wopmay, zone orogénique du début du Protérozoïque formée à la bordure ouest du craton des Esclaves d'âge archéen. Ce groupe de 4 km d'épaisseur comprend cinq formations, soit de la plus ancienne à la plus récente: 1) le grès de Beaverlodge Lake, conglomérat et grès à sédimentation subaérienne; 2) la formation de Zebulon, roches volcaniques calco-alcalines, produits d'une éruption subaérienne, variant du basalte à la rhyolite; 3) la formation de Conjuror Bay, roches silicoplastiques mises en place en milieu marin peu profond; 4) le basalte de Bloom, basalte tholéiitique en coussins; et 5) le gabbro de Fishtrap Lake, filons-couches et dykes de gabbro tholéiitique interprétés comme étant des roches comagmatiques avec le basalte de Bloom. Le groupe de Bell Island Bay repose en discordance sur un socle sialique (terrain de Hottah) et est recouvert en discordance par des roches volcaniques et sédimentaires d'arc continental de la zone magmatique de Great Bear.

Compte tenu de leur milieu de sédimentation, de leur composition chimique, du cadre tectonique régional et de leur analogie avec des roches datant du Mésozoïque à l'Holocène, les roches du grès de Beaverlodge Lake et de la formation de Zebulon font partie d'un arc magmatique continental, et la formation de Conjuror Bay, le basalte de Bloom et le gabbro de Fishtrap Lake sont liés à la formation d'un bassin marginal plus récent.

Les laves et intrusions tholéiitiques du groupe de Bell Island sont d'âge, de géochimie et de lithologie semblables aux groupes d'Akaitcho et de Grant, les unités stratigraphiques les plus basses de la zone interne de l'orogène de Wopmay, indiquant une corrélation entre ces trois groupes et une sédimentation au sein du même bassin. Selon cette hypothèse, l'orogène de Wopmay représenterait des épisodes de magmatisme et de tectonisme associés à une marge de plaque active de type andin, plutôt qu'un cycle de Wilson.

SUMMARY

The Bell Island Bay Group occurs in the western part of Wopmay Orogen, an early Proterozoic orogenic belt developed on the western margin of the Archean Slave Craton. The group unconformably overlies variably metamorphosed and deformed supracrustal and plutonic rocks of Hottah Terrane (1958-1902 Ma) and is unconformably overlain by rocks of the Great Bear Magmatic Zone (1878-1843 Ma). Chemical composition, magmatic evolution and regional tectonic setting support the conclusion that Hottah Terrane and the Great Bear Magmatic Zone represent continental magmatic arcs.

The Bell Island Bay Group has a maximum exposed thickness of 4 km and is divided into five formations. Beaverlodge Lake Sandstone, the oldest formation of the group, is a fining-upward sequence of volcanic conglomerate and arkosic and lithic sandstone. The formation is interpreted to represent a synvolcanic subaerially deposited alluvial fan complex. An assemblage of volcanic rocks, named the Zebulon Formation (1898 Ma), overlies and interfingers with the Beaverlodge Lake Sandstone. The formation comprises in ascending order: a lower member comprising mafic to intermediate aphyric lavas intercalated with minor rhyolitic block-and-ash flows and bedded tuff; a middle member of thick (350 m) rhyolite ash-flow tuff; and an upper member comprising several rhyolite flow-domes intercalated with minor mafic to intermediate flows. Overall, the rocks form a basalt-andesite-dacite-rhyolite suite. No plutonism directly related to this phase of magmatism is recognized, except for small hypabyssal intrusions.

Subsequent magmatism and sedimentation record a transition from a subaerial to a subaqueous depositional environment. The Conjuror Bay Formation, which conformably overlies the Zebulon Formation, contains rippled and cross-bedded mature quartzarenite and planar bedded siltstone and mudstone deposited in a marginal marine setting. Pillowed flows of Bloom Basalt overlie the sedimentary rocks and are intercalated with oolitic and stromatolitic patch reefs. Textures of the basalt range from aphyric to plagioclase megacrystic and glomerocrystic. Eruption in shallow water is suggested by the intercalated patch reefs and highly vesicular nature of the basalts. Fishtrap Lake Gabbro forms sills in the pillowed flows. Feeders to the flows and sills occur as north-trending gabbroic dykes that cut the sialic basement complex (Hottah Terrane).

Rocks of the Zebulon Formation form a continuous compositional suite from basalt to rhyolite. On an AFM diagram, they plot within the calc-alkaline field and exhibit no iron enrichment. For the basalt-andesite range, TiO_2 values (0.56-1.9%) are low and K_2O values (0.91-4.27%) and average Al_2O_3 contents (16.9%) are high. Of the REE, only analyses for La and Yb are available. La/Yb ratios

SOMMAIRE

Le groupe de Bell Island Bay se situe dans la partie ouest de l'orogène de Wopmay, zone orogénique du début du Protérozoïque formée dans la bordure ouest du craton des Esclaves d'âge archéen. Ce groupe repose en discordance sur les roches supracrustales et plutoniques variablement métamorphisées et déformées du terrain de Hottah (1958 à 1902 Ma) et est recouvert par des couches discordantes de roches de la zone magmatique de Great Bear (1878 à 1843 Ma). La composition chimique, l'évolution magmatique et le cadre tectonique régional appuient l'hypothèse selon laquelle le terrain de Hottah et la zone magmatique de Great Bear représenteraient des arcs magmatiques continentaux.

Le Groupe de Bell Island Bay, dont l'épaisseur maximale visible atteint 4 km, se divise en cinq formations. Le grès de Beaverlodge Lake, la formation la plus ancienne du groupe, est une séquence de conglomérat volcanique et de grès arkosique et lithique dont la granulométrie devient plus fine vers le haut. La formation est interprétée comme étant un complexe de cône alluvial synvolcanique à sédimentation subaérienne. Un assemblage de roches volcaniques, appelé formation de Zebulon (1898 Ma) repose sur le grès de Beaverlodge Lake tout en s'y interdigitant. La formation comprend dans l'ordre ascendant: un membre inférieur composé de laves aphyriques de nature mafique à intermédiaire dans lesquelles s'intercalent des coulées secondaires de blocs et de cendres rhyolitiques et du tuf stratifié; un membre intermédiaire de tuf épais (350 m) de cendres de coulée rhyolitiques; et un membre supérieur composé de plusieurs coulées et dômes rhyolitiques dans lesquels s'intercalent des coulées secondaires de nature mafique à intermédiaire. Globalement, les roches forment une série de basalte, andésite, dacite et rhyolite. Aucun plutonisme directement lié à cette phase de magmatisme n'a été relevé, sauf quelques petites intrusions hypabyssales.

Un magmatisme et une sédimentation ultérieurs attestent du fait que le milieu de sédimentation est passé de subaérien à subaquatique. La formation de Conjuror Bay qui repose en concordance sur la formation de Zebulon, contient du quartzite sédimentaire évolué à rides et à stratification oblique et du microgrès et des pélites à stratification plane mis en place dans un milieu marin de type marginal. Les coulées en coussins du basalte de Bloom reposent sur les roches sédimentaires et de petites constructions coraliennes oolitiques et stromatolitiques s'y intercalent. La structure du basalte varie d'aphyrique à phénocristalline et gloméro-blastique à plagioclase. L'éruption en eau peu profonde est révélée par les petites constructions récifales intercalées et la nature très vésiculaire des basaltes. Le gabbro de Fishtrap Lake forme des filons-couches dans les coulées en coussins. Les coulées et les filons-couches ont été alimentés par des dykes gabbroïques à direction nord qui recoupent le socle sialique (terrain de Hottah).

Les roches de la formation de Zebulon forment une série de composition continue qui varie du basalte à la rhyolite. Sur un diagramme AFM, elles se situent dans le champ calco-alcalin et n'affichent aucun enrichissement en fer. Pour la catégorie basalte et andésite, les teneurs en TiO_2 (0,56 à 1,9 %) sont faibles et les teneurs en K_2O (0,91 à 4,27 %) et les teneurs en Al_2O_3 (16,9 %) sont en moyenne élevées. En ce qui concerne les terres rares, des

range from 9 to 17 and overall abundances are high, indicating that the Zebulon Formation is LREE-enriched. Trace elements display several trends: 1) Rb, Ba, Zr, Y, Nb and Yb all correlate positively with SiO_2 content, albeit Yb very weakly; 2) Zr, Sr, Co and V display a negative correlation with SiO_2; 3) Cr, Ni and Cu have higher values in basalts, but decrease rapidly to a constant value for the andesite-rhyolite range; and 4) La is fairly constant, but more variable with increasing SiO_2 content. The basalts are LIL element (Sr, K, Ba, Rb) enriched and are depleted in high field strength elements (Nb, P, Zr, Ti, Y, Yb) relative to N-MORB.

Rocks of Bloom Basalt and Fishtrap Lake Gabbro are chemically indistinguishable and interpreted to be comagmatic based on field relationships, similar distinctive textures and chemistry. They range from olivine to quartz normative, plot within the tholeiitic field on an AFM diagram, have SiO_2 contents between 48.08 and 51.97% and are slightly evolved with total iron contents between 9.1 and 14.8%. Titanium contents (0.81-1.56%) are intermediate between averages for Cenozoic arc tholeiites and MORBs; they overlap with TiO_2 values for marginal basin basalts. Ni (57-160 ppm) and Cr (32-280 ppm) levels are relatively low and Rb (2-41 ppm), Ba (80-320 ppm) and K_2O (0.29-1.31%) contents are moderately high relative to Cenozoic N-type MORB. Overall, they are LIL-element enriched relative to MORB, with values similar to arc tholeiites and marginal basin basalts. However, it cannot be ruled out that some of the high and variable K, Ba, and Rb values are due to secondary alteration. Water content (1.70-3.80%), which may be primary, is higher than normal MORB but similar to marginal basin basaltic glasses. Average Zr/Y ratios (3.4) overlap those of ocean-floor basalt and arc tholeiites, but are lower than ratios for continental basalts. Ti, Y and Zr abundances are similar to modern oceanic tholeiites and plot on a Ti-Y-Zr diagram in the ocean-floor basalt field. La/Yb ratios (5.2-9.8) imply slight LREE enrichment, in contrast to the generally flat, or LREE depleted patterns of MORB. Ti/V ratios (20-50) overlap both island arc tholeiite and MORB ratios.

The Zebulon Formation is closely comparable in both chemical composition and style of volcanism to Cenozoic continental arcs. On a regional scale, the Zebulon Formation both overlies (Hottah Terrane) and is overlain by (Great Bear Magmatic Zone) volcanic-plutonic suites best interpreted as continental arcs. Spatially and temporally, the regional tectonic setting of the Zebulon Formation therefore is compatible with a continental magmatic arc.

analyses ne sont disponibles que pour La et Yb. Les rapports La/Yb varient de ? à 17 et leur concentration moyenne globale est élevée, indiquant que la formation de Zebulon est enrichie en éléments légers des terres rares. Les éléments en traces présentent plusieurs tendances: 1) Rb, Ba, Zr, Y, Nb et Yb correspondent tous positivement à une teneur en SiO_2, quoique Yb le soit très faiblement; 2) Zr, Sr, Co et V affichent une corrélation négative avec une teneur en SiO_2; 3) les teneurs en Cr, Ni et Cu sont élevées dans les basaltes, mais diminuent rapidement à une valeur constante dans la gamme andésite et rhyolite; et 4) la teneur en La est relativement constante mais varie lorsque celle en SiO_2 augmente. Les basaltes sont enrichis en éléments lithophiles (Sr, K, Ba, Rb) et pauvres en éléments à forte intensité de champ (Nb, P, Zr, Ti, Y, Yb) comparativement au basalte de la dorsale médio-océanique (BDMO) de type N.

Les roches du basalte de Bloom et du gabbro de Fishtrap Lake sont de composition chimique identique et semblent comagmatiques si l'on se fonde sur leur relation spatiale et leur similitude distinctive en matière de structure et de composition chimique. Ces roches variant de l'olivine au quartz normatif, se retrouvent dans le champ tholéiitique d'un diagramme AFM, ont une teneur en SiO2 entre 48,08 et 51,97 % et ont légèrement évolué avec une teneur en fer totale variant de 9,1 à 14,8 %. Les teneurs en titane (0,81 à 1,56%) sont intermédiaires se situant entre les teneurs moyennes des tholéiites d'arc cénozoïque et du BDMO; elles recoupent les teneurs en TiO_2 des basaltes de bassins marginaux. Les teneurs en Ni (57 à 160 ppm) et en Cr (32 à 280 ppm) sont relativement faibles et les teneurs en Rb (2 à 41 ppm), Ba (80 à 320 ppm) et K_2O (0,29 à 1,31 %) sont moyennement élevées comparativement au BDMO de type N du Cénozoïque. Dans l'ensemble, ces roches sont enrichies en éléments lithophiles comparativement au BDMO avec des teneurs semblables à celles des tholéiites d'arc et aux basaltes de bassins marginaux. Cependant, il est impossible de nier que certaines teneurs élevées et variables en K, Ba et Rb sont peut-être attribuables à une altération secondaire. Leur teneur en eau (1,70 à 3,80 %), qui est peut-être primitive, est plus élevée que dans le BDMO normal mais semblable à celle des verres basaltiques des bassins marginaux. Les rapports moyens de Zr/Y (3,4) recoupent ceux des basaltes de fond océanique et des tholéiites d'arc mais sont inférieurs à ceux des basaltes continentaux. La concentration moyenne en Ti, Y et Zr est semblable à celle des tholéiites océaniques actuelles et se situe, sur un diagramme Ti-Y-Zr, dans le champ du basalte de fond océanique. Les rapports La/Yb (5,2 à 9,8) indiquent un léger enrichissement en éléments légers des terres rares (ELTR) contrairement aux configurations généralement uniformes ou appauvries en ELTR du BDMO. Les rapports Ti/V (20 à 50) recoupent ceux de la tholéiite d'arc insulaire et du BDMO.

La formation de Zebulon est très comparable par sa composition chimique et son style de volcanisme aux arcs continentaux cénozoïques. une échelle régionale, la formation de Zebulon est à la fois sous-jacente (terrain de Hottah) et sus-jacente à la zone magmatique de Great Bear, séries volcaniques et plutoniques considérées comme des arcs continentaux. Spatialement et temporellement, le cadre tectonique régional de la formation de Zebulon est donc compatible avec l'existence d'un arc magmatique continental.

Marginal basin basalts are the one volcanic group that share all the salient features with Bloom Basalt and Fishtrap Lake Gabbro, such as: association with a change from calc-alkaline to tholeiitic magmatism; predominance of basaltic magmatism with chemistry transitional between mid-ocean ridge basalts and arc tholeiites; and eruption during extension, subsidence and marine innundation.

In conclusion, the Bell Island Bay Group can easily and logically be interpreted to represent volcanism within an extending and subsiding continental arc. However, there is no evidence that extensional processes led to the generation of oceanic crust. Overall, the tectonic setting of the Bell Island Bay Group is considered closely analogous to Mesozoic-Recent examples of continental arc-ensialic marginal basin pairs such as those documented in central Chili, southern Chili and the Okinawa Trough.

About 120 km east of the main exposures of the Bell Island Bay Group, in the easternmost zone of Wopmay Orogen, metavolcanic and metasedimentary rocks of the Akaitcho and Grant groups (1895-1902 Ma) occur at the base of the Coronation Supergroup. Based on similarities in lithology, chemistry and age, rocks of the Akaitcho and Grant groups are correlated with tholeiitic rocks of the Bell Island Bay Group (Bloom Basalt, Fishtrap Lake Gabbro). This implies that rocks of all three groups were deposited in the same marginal basin.

If the Bell Island Bay Group is not exotic with respect to the Slave Craton and the Coronation Supergroup, then the arc-like volcanic rocks of the Zebulon Formation resulted from easterly-directed subduction, as there was no ocean to the east. Extension within the arc led to the formation of an ensialic marginal basin between Hottah Terrane and Slave Craton. This supports a back-arc setting for the Coronation Supergroup. Therefore, Wopmay Orogen may represent tectonism and magmatism in an evolving Andean-type plate margin, rather than a Wilson Cycle.

Les basaltes de bassins marginaux sont les seules roches volcaniques présentant les mêmes caractéristiques prédominantes que le basalte de Bloom et le gabbro de Fishtrap Lake, notamment: une association avec un changement de la nature du magmatisme de calco-alcaline à tholéiitique; prédominance de magmatisme basaltique de composition chimique transitoire se situant entre les basaltes de dorsale médio-océanique et les tholéiites d'arc; et éruption durant les stades de distension, de subsidence et d'inondation marine.

En conclusion, le groupe de Bell Island Bay peut facilement et logiquement être interprété comme étant le résultat d'un volcanisme au sein d'un arc continental en distension et en subsidence. Cependant, il n'existe aucune trace des processus de distension qui auraient abouti à la formation d'une croûte océanique. Dans l'ensemble, le cadre tectonique du groupe de Bell Island Bay est considéré très analogue aux paires d'arc continental et de bassin marginal ensialique d'âge mésozoïque à holocène, comme celles qui ont été relevées au centre du Chili, au sud du Chili et dans la dépression d'Okinawa.

environ 120 km à l'est des principaux affleurements du groupe de Bell Island Bay, dans la zone interne de l'orogène de Wopmay, des roches métavolcaniques et métasédimentaires des groupes d'Akaitcho et de Grant (1895 à 1902 Ma) se trouvent à la base du supergroupe de Coronation. Fondé sur des similarités de lithologie, de composition chimique et d'âge, les roches des groupes d'Akaitcho et de Grant ont été corrélées aux roches tholéiitiques du groupe de Bell Island Bay (basalte de Bloom, gabbro de Fishtrap Lake). Il en découle que les roches des trois groupes ont été mises en place dans le même bassin marginal.

Si le groupe de Bell Island Bay n'est pas d'origine étrangère en ce qui concerne le craton des Esclaves et le reste de la marge Coronation, les roches volcaniques d'arc de la formation de Zebulon sont le produit d'une subduction dirigée vers l'est étant donné qu'il n'existait pas d'océan vers l'est. La distension au sein de l'arc a abouti à la formation d'un bassin marginal de nature ensialique entre le terrain de Hottah et le craton des Esclaves. C'est pourquoi la marge de Coronation devait se situer derrière un arc. L'orogène de Wopmay pourrait donc représenter des épisodes de tectonisme et de magmatisme associés à une marge de plaque active de type andin, plutôt qu'un cycle de Wilson.

INTRODUCTION

The early Proterozoic Great Bear Magmatic Zone has been interpreted as a continental magmatic arc generated by the eastward subduction of oceanic lithosphere (Hoffman and McGlynn, 1977; Hildebrand, 1981; Hildebrand et al., 1987b). In the vicinity of Hottah Lake, rocks of the Bell Island Bay Group (Reichenbach, 1985a), previously considered to be among the oldest of the zone, comprise subaerial lavas overlain by pillow basalts (McGlynn, 1976; Hoffman and McGlynn, 1977; Hildebrand, 1984a). However, a poorly understood stratigraphy coupled with a lack of age constraints for these volcanic rocks prevented reliable correlations which in turn obscured their regional significance. In addition, the occurrence of a thick succession of pillow basalts is atypical of a continental arc and the previously proposed tectonic setting of the basalts is therefore subject to speculation.

Rocks of the Bell Island Bay Group have been previously mapped only on a reconnaissance scale (McGlynn, 1976, 1979; Hildebrand et al., 1983, 1984); therefore, the author mapped them at 1:16 000 scale as the field component of an M.Sc. thesis study (Reichenbach, 1986b). The principal objectives of the study were to:

1. produce a detailed geological map and document the stratigraphy and structure of the volcanic succession;
2. characterize the rocks chemically and compare them with younger rocks from well-understood tectonic environments;
3. determine the age of the succession and thereby aid in regional correlations;
4. interpret the tectonic setting(s) of the group, and propose a regional tectonic model.

Earlier work in the study area includes that of Kidd (1936), McGlynn (1976, 1979), Wilson (1979) and Hildebrand et al. (1983, 1984).

Acknowledgments

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Regional geology

The Bell Island Bay Group outcrops along the western part of the early Proterozoic Wopmay Orogen, a north-trending orogen that developed on the western side of the Archean Slave Craton. The orogen can be divided into three major tectonic zones (Fig. 1), from west to east: Hottah Terrane, Great Bear Magmatic Zone and Calderian Accretionary Wedge.

Hottah Terrane comprises deformed metasedimentary and metavolcanic rocks cut by both deformed intermediate plutons and undeformed leucogranites (Hildebrand and Roots, 1985) and extends eastward beneath most of the Great Bear Magmatic Zone (Hildebrand et al., 1987a). The igneous rocks form the oldest recognized magmatic suite (1958-1902 Ma) in Wopmay Orogen (McGlynn, 1979; Hildebrand et al., 1983; Bowring, 1985). All ages quoted in this report are based on U-Pb (zircon) data. The presence of intermediate volcanic rocks and biotite-hornblende-bearing plutons suggests that Hottah Terrane represents a continental magmatic arc either contiguous to (Hildebrand and Roots, 1985) or allochthonous with (Hildebrand, 1981; Hildebrand et al., 1983) the western margin of Slave Craton prior to 1900 Ma.

The Bell Island Bay Group unconformably overlies Hottah Terrane. The group is a complex sequence of sedimentary rocks, subaerial basaltic to rhyolitic lava flows, ash-flow tuff, pillow basalts and hypabyssal gabbro sills regionally metamorphosed to subgreenschist facies. The Bell Island Bay Group extends from Conjuror Bay to Beaverlodge Lake (Hildebrand et al., 1983; Hildebrand and Roots, 1985; Reichenbach, 1985a) (Fig. 1). In the Conjuror Bay area the group lies unconformably beneath Moose Bay Tuff of the LaBine Group (Hildebrand, 1982, 1984a,b), the oldest ash-flow tuff exposed in that area.

The easternmost zone of the orogen, the Calderian Accretionary Wedge, comprises in ascending order: 1) metavolcanic and metasedimentary rocks of the Akaitcho Group, interpreted by Easton (1982) to represent rocks deposited within a continental rift; 2) a west-facing sedimentary prism which laps eastward onto Slave Craton and comprises the siliciclastic Odjick Formation overlain by the dolomitic Rocknest Formation (Hoffman, 1972, 1973; Grotzinger and Hoffman, 1983; Grotzinger, 1986); and 3) an eastwardly-migrating synorogenic foredeep (Hoffman, 1980a, 1981). These rocks, collectively termed the Coronation Supergroup (Hoffman, 1981), were detached from their basement, tectonically thickened, folded and thrust eastward onto Slave Craton (Tirrul, 1983; Hoffman et al., in press) during what is termed the Calderian Orogeny (St-Onge et al., 1983; Hoffman and Bowring, 1984). During the orogeny a suite of syntectonic to posttectonic plutons (Hepburn Batholith) was emplaced into the Coronation Supergroup and generated regional metamorphic aureoles (Lalonde, 1984; St-Onge et al., 1984; St-Onge, 1987). The orogeny, and postulated synchronous deformation of Hottah Terrane, has been interpreted as resulting from either collision of the Slave Craton with an exotic Hottah Terrane (Hildebrand, 1981; Hildebrand et al., 1983), or closure of a marginal basin existing between Slave Craton and Hottah Terrane (Hildebrand and Roots, 1985). U-Pb (zircon) ages (Bowring, 1985) bracket the deformation of the Calderian Accretionary Wedge between 1900 Ma (upper Akaitcho Group) and 1880 Ma (posttectonic Hepburn plutons).

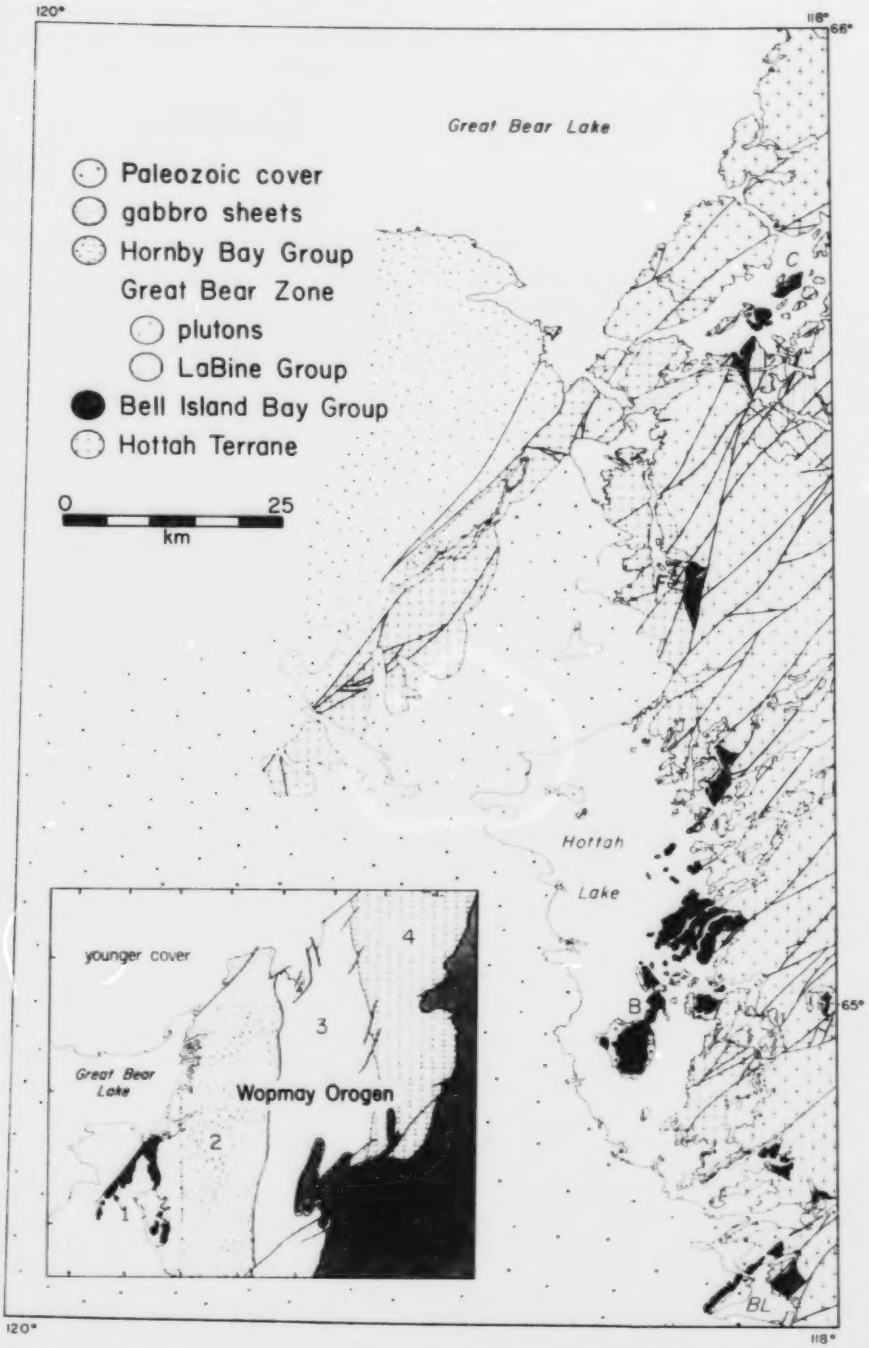

Figure 1. Generalized geological map showing the distribution of Hottah Terrane, Bell Island Bay Group, LaBine Group, plutons of the Great Bear Magmatic Zone, Hornby Bay Group and gabbro sills (modified from Hildebrand et al., 1983, 1984). C=Conjuror Bay, F=Fishtrap Lake, B=Bell Island, BL=Beaverlodge Lake. Inset map shows the location of Wopmay Orogen and its tectonic zones with respect to Slave Province. 1, Hottah Terrane and Bell Island Bay Group; 2, Great Bear Magmatic Zone; 3 and 4, Calderian Accretionary Wedge comprising 3, Hepburn metamorphic-plutonic zone and 4, Asiak thrust-fold belt.

The Great Bear Magmatic Zone contains the youngest magmatic suites (1878-1843 Ma; Bowring, 1984) exposed in the orogen. It is a 100 km wide, north-trending linear belt that outcrops over a strike length of 450 km and unconformably overlies the Bell Island Bay Group to the west (this report) and both Archean basement (Easton, 1982; Hoffman, 1984b) and granites of Hottah Terrane to the east (Hildebrand et al., 1987a). The north-trending Wopmay Fault Zone, which is a belt of mylonites and brittle faults (King et al., 1983; Hoffman, 1984a; King, 1985), approximately coincides with the inferred boundary between the Calderian Accretionary Wedge and Hottah Terrane. The oldest rocks of the Great Bear Magmatic Zone occur along its western and eastern margins (Hildebrand et al., 1987a,b); rocks in the central part of the zone are younger, and the overall structure of the Great Bear zone is therefore interpreted to be synclinal (Hildebrand and Bowring, 1984; Hildebrand et al., 1987b). The magmatic suite is calc-alkaline, and the volcanic rocks range continuously from basalt to rhyolite, forming a typical basalt-andesite-dacite-rhyolite series (Hildebrand, 1982; Hildebrand and Bowring, 1984; Hildebrand et al., 1987b). The linear trend of the Great Bear Magmatic Zone, overall synclinal structure, regional tectonic setting, chemical composition and magmatic evolution all support the conclusion that the Great Bear Magmatic Zone represents a continental magmatic arc related to easterly-directed subduction (Hildebrand, 1982; Hildebrand et al., 1987b).

All rocks of western Wopmay Orogen, except for syenogranite plutons of the Great Bear Magmatic Zone emplaced between 1850-1840 Ma (Bowring, 1985), are broadly folded about gently-plunging axes, generally of northwest trend and oblique to the overall trend of the zone (Hoffman and McGlynn, 1977). The oblique trend and en echelon character of the folds suggest a dextral transpression of the zone (Hoffman, 1980a; Hildebrand, 1981) attributed to oblique ridge subduction (Hildebrand, 1983; Hildebrand, et al., 1987b). U-Pb (zircon) ages bracket this deformation between 1860 Ma (the age of the youngest known folded rocks) and 1850 Ma (the age of the oldest known postfolding syenogranite plutons; Bowring, 1984).

Rocks in the western part of the orogen are cut by nearly vertical, northwest-trending dextral transcurrent faults which have up to 15 km of strike-slip displacement (Hoffman and McGlynn, 1977). The faults are but one domain of a much larger regional set of transcurrent faults that extends throughout Wopmay Orogen (Hoffman, 1980a,b, 1984b) and adjacent parts of the northwestern Canadian Shield. The fault system is the result of east-west compression (Tirrul, 1984) interpreted to originate from a 1810-1850 Ma collision along the western margin of Hottah Terrane (Hoffman et al., 1982; Hildebrand et al., 1987b). In the eastern part of the orogen conjugate sets of faults occur and are compatible with a regional pure shear model (Tirrul, 1984).

STRATIGRAPHY

The Bell Island Bay Group, which unconformably overlies Hottah Terrane, is an assemblage of lava flows, sedimentary rocks and hypabyssal intrusions characterized by complex interfingering and intrusive relationships typical of most volcanic terranes. The group, which has a maximum exposed thickness of 4 km, is here divided into five formations, from oldest to youngest: Beaverlodge Lake Sandstone, Zebulon Formation, Conjuror Bay Formation, Bloom Basalt and Fishtrap Lake Gabbro. Hildebrand (1982, 1984a) named the Conjuror Bay Formation and Bloom Basalt and included them in the LaBine Group; the other formations are newly named in this report. However, in the Conjuror Bay area, the subaqueous Bloom Basalt is overlain with angular unconformity by subaerial Moose Bay Tuff of the LaBine Group. In this report it is proposed to remove the Conjuror Bay Formation and Bloom Basalt from the LaBine Group and include them within the Bell Island Bay Group. The upper boundary of the Bell Island Bay Group is placed at the top of Bloom Basalt (Reichenbach, 1985a).

The known regional extent of the Bell Island Bay Group is from Conjuror Bay to Bea erlodge Lake (Fig. 1). Figure 2, in pocket, is a detailed geological map showing the major lithostratigraphic units of the Bell Island Bay Group in the Hottah Lake area. Other exposures of the group, to the north and south of Hottah Lake, are discussed elsewhere (Hildebrand et al., 1983; Hildebrand, 1984a; Hildebrand and Roots, 1985). Table 1 presents the stratigraphic nomenclature and Figure 3 shows the major units, their thicknesses and probable correlations within the group.

The present report is based on a total of four months of field work during the summers of 1983 and 1984. Mapping was done on 1:16 000 black-and-white aerial photographs enlarged from standard 1:63 360 photographs; the data were compiled on 1:25 000 topographic maps. Petrographic interpretations are based on a study of approximately 250 thin sections. Because most of the rocks in the study area are either aphyric or only sparsely porphyritic, names are based upon chemical composition where possible. The volcanic rocks have been divided on the basis of their volatile-free SiO2 content as follows:

basalt 53% SiO_2

andesite 53-62% SiO_2

dacite 63-69% SiO_2

rhyolite 69% SiO_2

These divisions are slightly modified from Peccerillo and Taylor (1976) and Gill (1981), but coincide closely with names used in the study area based on textures, flow layering and devitrification features, estimated density and phenocryst content. Where chemical analyses are not available, the rocks have been classified on the basis of petrographic similarity to analyzed samples. The terminology for ash-flow tuffs is that of R.L. Smith (Smith, 1960; Ross and Smith, 1961), and grain size of pyroclasts is that of Fisher (1961) and Schmid (1981).

Table 1. Table of formations

Eon Era	Terrane	Group	Formation/ Lithodeme	Member	Map Symbol	Lithology
Phanerozoic					q	Glacial drift
	unconformity					
			Old Fort Island		Cof	Conglomerate, sandstone
	unconformity					
mid Prot			gabbro		g	medium- to coarse- grained gabbro
Early Proterozoic	intrusive contact					
	Great Bear Magmatic Zone		Yen pluton		Y	granodiorite, monzogranite
		intrusive contact				
		LaBine				lava flows, ash-flow tuff, sedimentary rocks
	unconformity					
		Bell Island Bay	Fishtrap Lake Gabbro		BF	gabbro, diabase
			intrusive contact			
			Bloom Basalt	dacite	BBd	dacite flow and flow breccia
					BB	pillow basalt, breccia, hyalotuff
			Conjuror Bay	upper	BCu	mudstone, siltstone, sandstone
				lower	BCl	conglomerate, quartzarenite
			Zebulon	upper	BZU	predominantly rhyolitic lavas and breccias
				middle	BZM	rhyolitic and dacitic ash-flow tuff
				lower	BZL	mafic to silicic lavas and breccias, bedded tuff
			Beaverlodge Lake Sandstone		BL	sandstone, conglomerate siltstone
	unconformity					
	Hottah				H	metavolcanic, metasedimentary rocks; deformed, non-deformed plutons

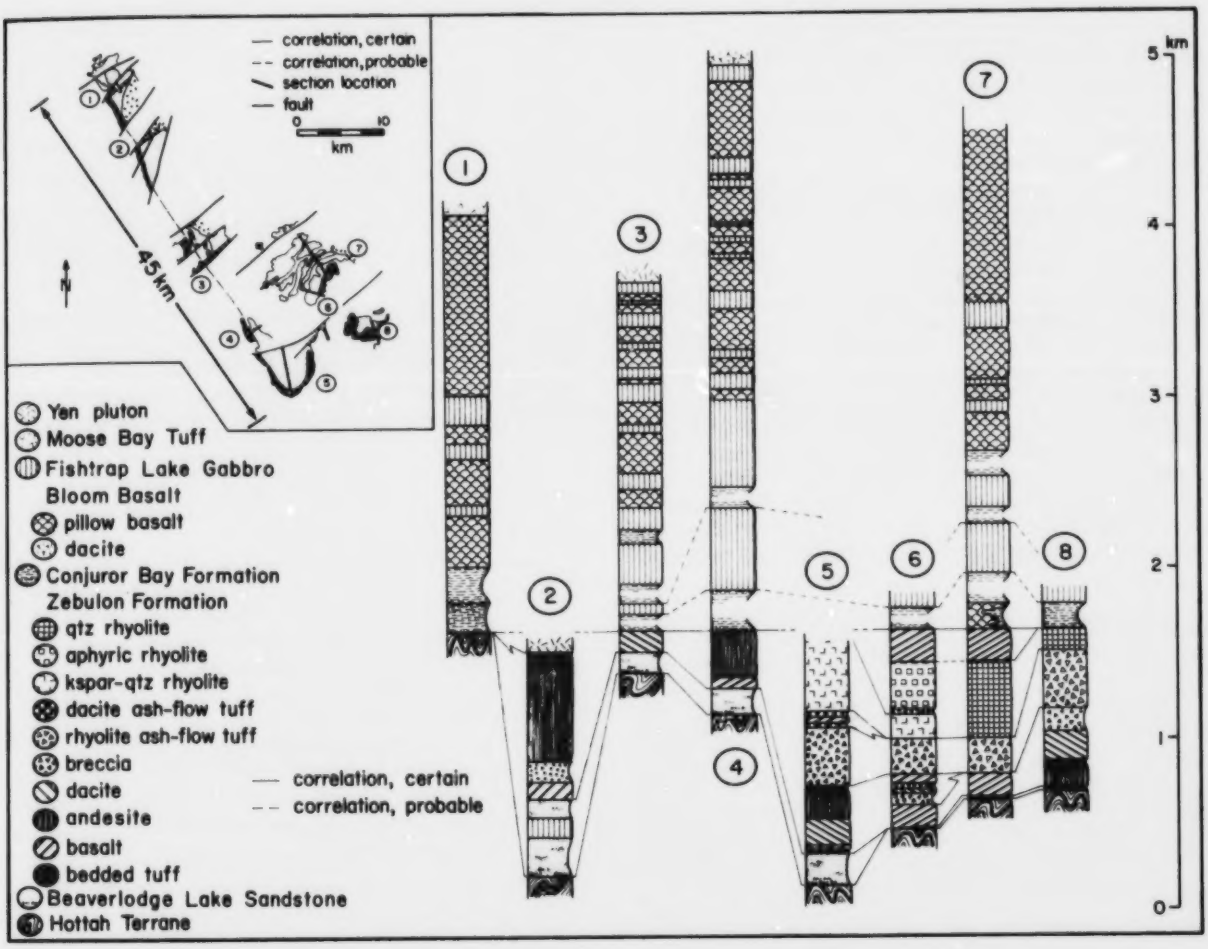

Figure 3. Stratigraphic sections of the Bell Island Bay Group. Inset diagram shows the location of sections after strike-slip separation on the transcurrent faults is restored: Black, Hottah Terrane; dotted pattern, Bell Island Bay Group; ticked pattern, Great Bear Magmatic Zone.

Beaverlodge Lake Sandstone

The name Beaverlodge Lake Sandstone is proposed here for a fining-upward sequence of conglomerate and sandstone that overlies Hottah Terrane from Fishtrap to Beaverlodge lakes. The basal contact is an erosional unconformity which is typically well exposed (Fig. 4). Upper parts of the sandstone interfinger with intermediate and silicic lavas. Although most of the known exposures of the formation occur in a strip from Beaverlodge to Fishtrap lakes, some isolated exposures occur as roof pendants in granodiorite near the mouth of the Zebulon River (Hildebrand and Roots, 1985). The best exposures and most complete sections occur along eastern and southern Bell Island. The total thickness of the formation increases westward from less than 1 m to 200 m (Fig. 3).

Coarse grained, poorly bedded to massive, polymictic clast-supported conglomerate generally occurs at the base of the formation. The conglomerate contains angular to subrounded clasts, up to 15 cm across, of flow-layered silicic

Figure 4. Lithic sandstone and conglomerate of the Beaverlodge Lake Sandstone, Bell Island Bay Group, unconformably overlying gneiss of the Hottah Terrane. Hammer (35 cm long) head rests on the unconformity. GSC 204113-P.

volcanic rocks, vein quartz, basement granitoids, mafic sedimentary rocks, jasper and angular potassium feldspar fragments up to 4 cm in size (Fig. 5). Volcanic rocks account for at least one third of the total fragments. Locally, discontinuous beds (30-50 cm thick) contain vein quartz pebbles to near exclusion of anything else (Fig. 6). At a few localities on eastern Bell Island, the conglomerate is underlain by 1-5 m of medium grained sandstone to arkosic granulestone, with discontinuous beds 1-15 cm thick marked by changes in grain size. Some of the beds contain imbricated pebbles (up to 6 cm) interpreted as lag deposits. Diffuse heavy mineral bands accentuate trough cross-bedding.

Overlying the conglomerate is a fining-upward sequence of fine to medium grained lithic arkose. Granulestone beds occur throughout, but decrease in abundance up section. The sequence is well bedded; individual beds are normally graded and are 3-5 cm thick. Trough cross-beds are ubiquitous (Fig. 7) and indicate paleocurrents to the west-southwest. Local channels filled in with conglomerate occur in the granulestone and are in the range of 4-5 m wide by 1-2 m deep.

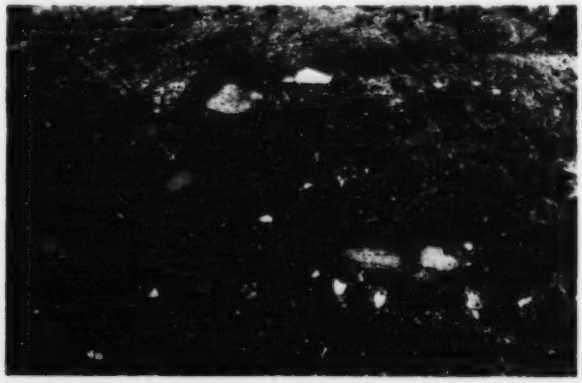

Figure 5. Polymictic conglomerate near the base of the Beaverlodge Lake Sandstone. Note scale in upper right of photo. GSC 204113-E.

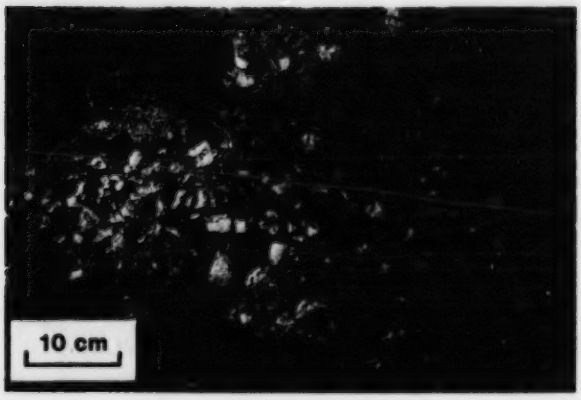

Figure 6. Quartz pebble conglomerate fills a channel in the Beaverlodge Lake Sandstone, eastern Bell Island. GSC 204400.

On eastern and southern Bell Island, a well-bedded, generally fining-upward volcaniclastic unit (up to 8 m thick) occurs at the top of Beaverlodge Lake Sandstone. Beds 1 mm to 3-4 cm thick consist of alternating volcanogenic siltstone and wacke. The matrix of the wacke weathers dark grey, or in places where it is hematized, dark purple, and is contrasted by angular red volcanic fragments and crystals of quartz, potassium feldspar and plagioclase. Sandstone lenses occur within the siltstone. Trough cross-bedding, scours, angular rip-ups of the siltstone and slumps are common.

Based on sedimentary structures (channels, grading, cross-stratification), lateral and vertical changes in lithology and grain size and overall immaturity, Beaverlodge Lake Sandstone is interpreted to be a subaerial alluvial fan complex (cf. Nilsen, 1982; Hildebrand et al., 1983; Reichenbach, 1985a). Both the predominance of volcanic fragments and the intercalation of upper parts of the sequence with lava flows indicates that sedimentation was synchronous with volcanism.

Zebulon Formation

The name Zebulon Formation is proposed here for a 1.5 km thick, complex sequence of volcanic rocks and minor intercalated volcaniclastic units that conformably overlie and locally interfinger with Beaverlodge Lake Sandstone. The regional extent is from Fishtrap Lake to Beaverlodge Lake. The best exposures and most complete sections occur on Bell Island and in the synclines and anticlines on the mainland directly to the east and northeast of Bell Island.

The formation comprises a lower member of aphyric mafic to silicic lavas and breccias, a middle member of rhyolite and dacite ash-flow tuff and an upper member of aphyric to porphyritic rhyolite flow-domes.

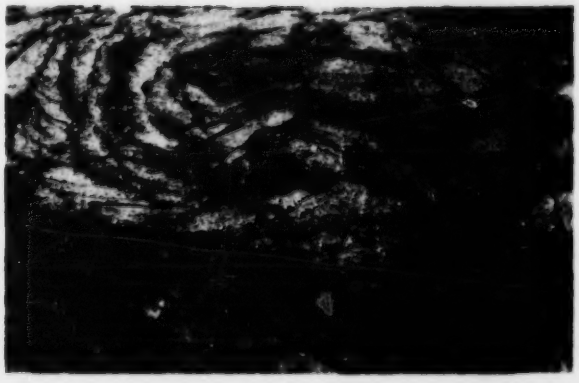

Figure 7. Trough cross-beds in the upper part of the Beaverlodge Lake Sandstone, southern Bell Island. Pen is 15 cm long (location indicated by arrow). GSC 204113-I.

Lower member

The lower member is a varied sequence of subaerially erupted lava flows, volcanic breccias and minor tuffs and volcaniclastic rocks. The most striking feature of the lava flows is their predominantly aphyric nature. Only a few flows contain sparse plagioclase or quartz phenocrysts. In lieu of phenocryst assemblages, the criteria for distinguishing individual lava flows in the field were basal and flow-top breccias, distribution of amygdules and intercalated pyroclastic and volcaniclastic rocks. Chemical compositions generally agreed with field names and range from basalt to rhyolite with andesitic to dacitic compositions the most prevalent. Due to complex interfingering relationships among flows and variations along strike, the stratigraphic order of the units within the lower member is unclear and the distinction of individual units is based solely on lithology.

Exposures of the lower member occur in the vicinity of Fishtrap Lake and Beaverlodge Lake, on Bell Island and on the mainland to the east and northeast of Bell Island. The contact with the underlying Beaverlodge Lake Sandstone is conformable and placed at the base of the lowest lava flow or tuff. Rip-up clasts of sedimentary rocks occur in the basal portions of the lavas where they are in contact with the Beaverlodge Lake Sandstone.

Basalt

Aphyric basalt flows with amygdaloidal basal portions outcrop continuously for a strike length of several kilometres along eastern Bell Island, northern Bell Island and also on the mainland to the northeast of Bell Island (PZ-lb, Fig. 2). The maximum total thickness of the unit is 100 m, but individual flows could not be mapped.

In thin section, original igneous textures are well preserved, although primary mineral assemblages have been variably altered. The basalts are holocrystalline with subophitic to intersertal textures. One flow contains fractured microphenocrysts of olivine altered to serpentine and chlorite; all other flows are aphyric. In the groundmass, plagioclase occurs as euhedral laths, displays Carlsbad and albite twinning and in some flows defines a weak pilotaxitic texture. The plagioclase is slightly to intensely altered to saussurite, sericite and carbonate. No fresh pyroxene is present, but anhedral clots of uralite, chlorite and carbonate suggest its former presence. Fine grained iron-titanium oxide crystals are scattered throughout all thin sections.

Andesite

Lavas of andesitic composition outcrop in all areas where the lower member is exposed and at all stratigraphic positions within the member (PZ-la, Fig. 2). Along western Bell Island, there are two 40 m thick andesite flows intercalated with similar thicknesses of Beaverlodge Lake Sandstone. Along eastern Bell Island, and on the mainland to the east and northeast of Bell Island, the andesite flows are intercalated with basalt and dacite flows of the lower member. Basal portions of the andesites are coarsely flow layered or are platy jointed, becoming more massive higher in the flow. The weathered colour is highly variable and ranges from dark grey to dark purplish-brown. Quartz, chlorite and carbonate amygdules are plentiful, and in places are elongate, presumably parallel to flow direction (Fig. 8).

Many of the andesites are similar to the basalts in texture, mineralogy and alteration, except that the andesites lack olivine, contain a higher percentage of groundmass plagioclase and generally are sparsely (1-2%) microporphyritic, although one flow on northern Bell Island contains at least 15% plagioclase microphenocrysts (Fig. 9). Flow structures defined by aligned euhedral plagioclase microlites are well developed (Fig. 10 and 11). Euhedral to subrounded, blocky and lath-shaped plagioclase phenocrysts, ranging from 0.5-1.5 mm, are set in a subophitic to cryptocrystalline matrix. The plagioclase is zoned and has an internal sieve texture (Fig. 12). Low-silica andesites that occur on western Bell Island contain sparse uralitized pyroxene phenocrysts up to 2.5 mm. Hornblende and/or biotite have not been positively identified, but opacitic patches appear to be pseudomorphs

Figure 8. Andesite flow of the Zebulon Formation, with elongate, quartz-filled amygdules inferred to be parallel to flow direction, eastern Bell Island. Pen is 12 cm long. GSC 204113-K.

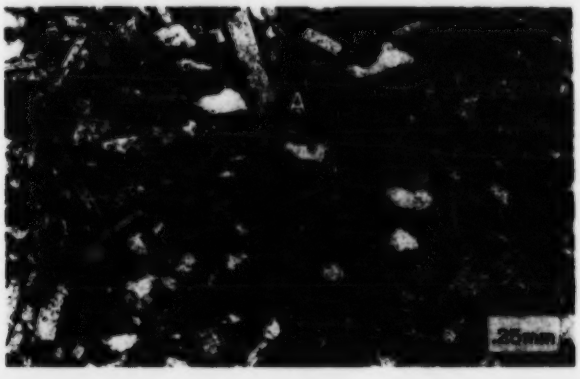

Figure 9. Abundant small phenocrysts of plagioclase, opacitic amphibole (A) and Fe-Ti oxides occur in the cryptocrystalline groundmass of an andesite flow of the Zebulon Formation. Note chlorite amygdule (C) in upper right corner.

after these minerals (Fig. 9). Iron-titanium oxides occur as fine grained euhedra to finely disseminated dust, the latter accounting for the dark grey colour of many andesite flows.

Dacite

The dacite flows of the lower member outcrop on Bell Island and on the mainland to the east and northeast of Bell Island (PZ-ld, Fig. 2). They interfinger with the other units in the lower member and are not constrained to a particular stratigraphic horizon. Weathering colour is varied, but many of the flows are oxidized to a brick red. Lower portions of the flows are coarsely flow layered (Fig. 13) parallel to local bedding. Flow-top breccias dispiaying devitrification and hydration features such as spherulites and perlitic fractures are common (Fig. 14). On central Bell Island, one dacite flow is at least 150 m thick with well-developed columnar jointing (Fig. 15), and may be a ponded or an intracanyon flow.

Original igneous textures and mineralogy in the dacites are somewhat obscured by devitrification and alteration. The dacites are predominantly aphyric. A few thin sections contain sparse corroded quartz phenocrysts. Others contain less than 1% flow-aligned plagioclase microphenocrysts

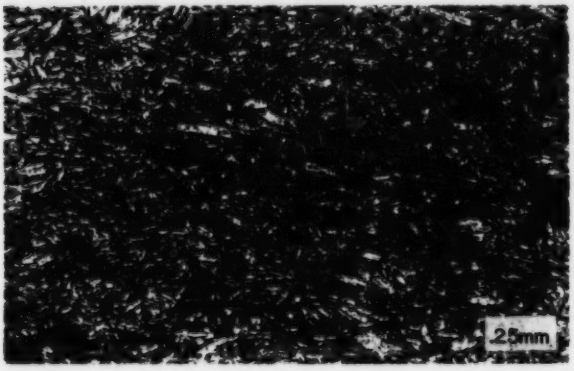

Figure 10. Pilotaxitic texture in holocrystalline andesite, Zebulon Formation, containing small black Fe-Ti oxide euhedra.

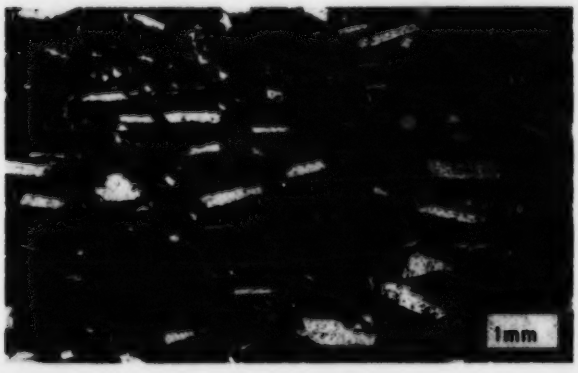

Figure 11. Flow-aligned plagioclase laths surrounded by cryptocrystalline matrix in andesite flow, Zebulon Formation.

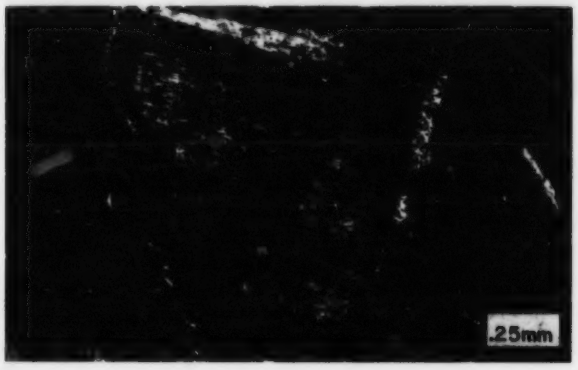

Figure 12. Zoned plagioclase phenocryst exhibits internal sieve texture in andesite flow, Zebulon Formation.

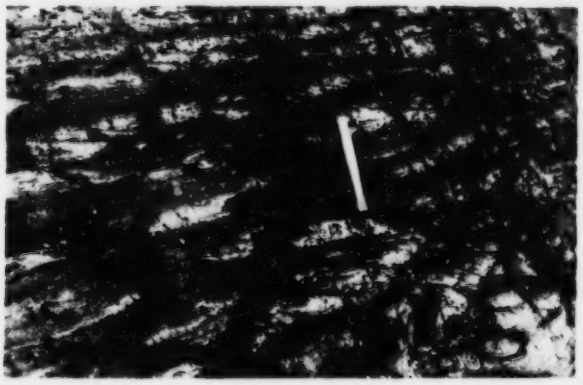

Figure 13. Dacite lava of Zebulon Formation, showing flow layering which is parallel to regional bedding near the base of the flow. Hammer is 35 cm long. GSC 204113-J.

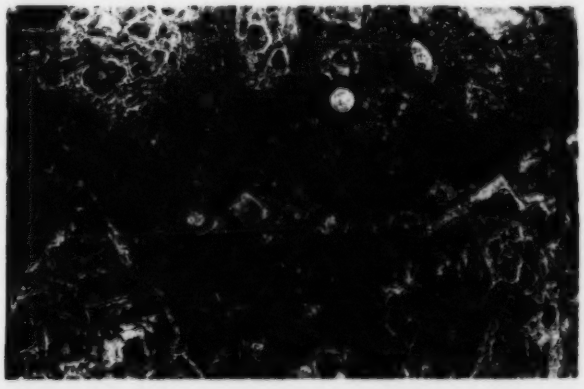

Figure 14. Autobrecciated dacite flow with perlitic fractures, Zebulon Formation, southern Bell Island. Diameter of coin is 2 cm. GSC 204113-N.

0.25-0.5 mm in size. The groundmass is a dense cryptocrystalline assemblage of quartz, alkali feldspar, sericite and iron-titanium oxides. Most thin sections exhibit a pervasive reddish stain due to finely disseminated hematite. Perlitic fractures (Fig. 16), spherulites and flow banding are common and occur in many thin sections. The devitrification and hydration textures suggests that the dacite flows were partly glassy when extruded.

Rhyolite

Although rhyolite flows are uncommon in the lower member, the occurrence of rhyolite breccias indicates that silicic magmatism probably occurred during eruption and deposition of the lower member. Rhyolite breccias have the same distribution as the previously described lavas and occur at all stratigraphic horizons within the lower member.

A distinctive sequence of brick-red weathering, monolithologic rhyolite breccias occurs along eastern Bell Island. At its northern extent, it conformably overlies the bedded tuff unit, and at its southern extent it interfingers with andesite and dacite lava flows, as does the bedded tuff. The sequence outcrops along strike for 2 km and is up to 53 m thick. The breccia sequence contains at least 8 units of variable thickness (1-10 m), each with sharp lower and upper contacts. Within each of these units are two subunits: 1) a lower tuff that is locally thinly bedded (0.5-5 cm), weathers light green and consists of red and green volcanic lapilli in an ashy matrix; and 2) an upper breccia with an excellent inversely graded base marked by a decrease in the amount of matrix and an increase in fragment size (Fig. 17). The contact between the lower tuff and upper breccia subunits varies from sharp (Fig. 17) to diffuse. The dominant fragments of the entire sequence are subangular to subrounded red rhyolitic blocks and boulders that are flow layered, spherulitic, aphyric and amygdaloidal. Lower units also contain angular dark green cryptofelsite fragments (up to 12 cm) and sparse vein quartz and granitoid fragments. In thin section, the volcanic fragments contain sparse (one per thin section) quartz and feldspar phenocrysts set in a cryptocrystalline matrix. Fragment size is greatest in the uppermost units, where rhyolitic blocks and boulders are commonly 1.5 m across. This masks the fragmental nature of the upper units, because the fragments are so large and the matrix is so sparse, that at first glance the breccia resembles a lava flow.

Figure 15. Columnar-jointed dacite flow about 150 m thick, in Zebulon Formation, southern Bell Island. GSC 204113-U.

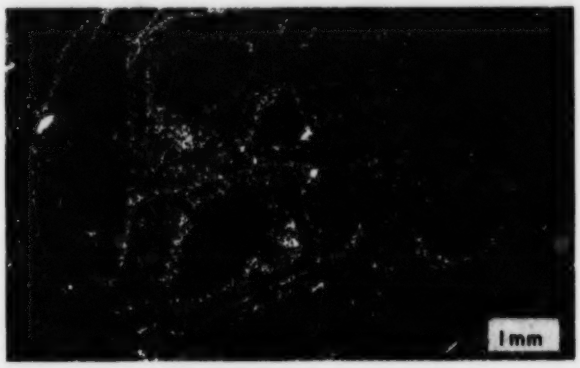

Figure 16. Photomicrograph of perlitic fractures in formerly glassy dacite flow, Zebulon Formation.

Figure 17. Air-fall tuff overlain by inversely graded rhyolite block-and-ash flow, Zebulon Formation. Pen is 15 cm long. GSC 204113-T.

These units are interpreted as repetitive cycles of air-fall tuff overlain by block-and-ash flows. The explosive event linked to the air-fall tuff possibly triggered collapse of a rhyolite dome which resulted in block-and-ash flows. The block-and-ash flows are similar to those described by Perret (1935) and Westercamp and Traineau (1983) from Mount Pelée, and to one example the author has seen in California which erupted from Panum Crater (Mono Craters) about 400 years ago. The red fragments are interpreted to be of similar composition to the green fragments based on similar petrology and analogy with Cenozoic ash-flow tuff and rhyolite flows (Williams, 1960; Crandell and Mullineaux, 1973). The red fragments probably represent finely crystalline material from the stony interior of the dome that oxidized and devitrified during cooling, and the green fragments probably represent the quenched glassy exterior.

Based on stratigraphic position and similarity of mineralogy and chemistry, a possible exposed rhyolite source for the block-and-ash flows is several kilometres to the west (Fig. 2, PZ-ur1), after separation along the transcurrent faults is restored. Alternatively, the block-and-ash flows may be related to a more proximal unexposed or eroded rhyolite dome. Similar but more massive rhyolite breccias are intercalated with dacite flows on the mainland to the east of Bell Island and may also be block-and-ash flows.

Bedded tuff

Light green weathering, dacitic to rhyolitic, well-bedded tuff is almost continuously exposed along eastern and southern Bell Island, and is discontinuously exposed on central Bell Island and on the mainland to the east and northeast of Bell Island. On eastern Bell Island it forms the lowest stratigraphic unit of the Zebulon Formation and conformably overlies Beaverlodge Lake Sandstone. On central Bell Island it occurs above the base of the formation and interfingers with lava flows. The maximum thickness of the unit is about 12 m. Beds generally range from several millimetres to three centimetres thick, although locally more massive beds are 0.5-2 m thick. Beds have sharp to gradational contacts defined by differences in grain size. Porcellanite beds alternate with lithic-rich beds containing lapilli and blocks in a fine grained tuffaceous matrix. Beds show normal and reverse grading. Most lithic fragments are less than 1 cm, but some coarse grained beds contain fragments up to 6 cm. Fragments include crystals of potassium feldspar and clear quartz and angular lithic clasts of red flow-layered volcanic rocks and dark green cryptofelsite, the latter flattened parallel to bedding in the thicker (15 cm-2 m), coarser grained beds.

Based on the siliceous composition, a well-bedded and graded nature, the overall fine grain size of the unit and the presence of phenocrysts and welded formerly glassy fragments, this unit is interpreted to comprise predominantly Plinian air-fall tuff, with small volume, welded pyroclastic flows occurring within the air-fall tuff.

Middle member

Three to four hundred metres of siliceous ash-flow tuff, termed the middle member, conformably overlies the lower member of the Zebulon Formation. The member is divided into two units, a lower rhyolite ash-flow tuff (PZ-mr, Fig. 2) and an upper dacite ash-flow tuff (PZ-md, Fig. 2). The only complete section is exposed on central Bell Island. Exposures of the rhyolite ash-flow tuff are excellent on the mainland to the east of Bell Island, but the middle member pinches out abruptly to the west and is completely absent on both western and northern Bell Island.

Locally exposed at the base of the middle member is 2-4 m of well-bedded inversely graded tuff, containing angular red aphyric volcanic fragments (less than 1 cm) and quartz, that mantles the irregular upper surface of lava flows of the lower member. This unit is interpreted as a Plinian air-fall premonitor to the overlying rhyolite ash-flow tuff.

Overlying the air-fall tuff (or lava flows of the lower member where the air-fall tuff is absent) is a mineralogically zoned, lithic-poor, terracotta weathering, simple cooling unit of rhyolite ash-flow tuff. The maximum thickness is about 350 m. Only in the anticline to the northeast of Bell Island is there an anomalous 12 m thick section of well-bedded volcanogenic siltstone, sandstone and conglomerate intercalated with the ash-flow tuff for a strike length of 200-300 m (Fig. 2). This may suggest that the tuff is a multiple depositional unit, or that an unrecognized fault has repeated the rhyolite ash-flow tuff (as happens directly to the north, see Fig. 2).

The lower 0.5-1 m of the tuff is light to very dark green. This grades upward into a coarsely spherulitic zone within one-half to several metres above the base. Coalesced spherulites, individually up to 15 cm in diameter, occur in continuous contact with one another for several metres upward in the tuff (Fig. 18). Lithophysal cavities, up to 15 cm in diameter and filled with quartz euhedra, are concentrated in the spherulitic horizon and also toward the top of the tuff. The spherulitic horizon is interpreted as the transition zone between the vitrophyric base and completely devitrified interior of the tuff, based on similar zonation seen in Cenozoic ash-flow tuffs of the San Juan volcanic field (P.W. Lipman, pers. comm., 1985) and Yellowstone Plateau (R.L. Christiansen, pers. comm., 1985).

Flattened dark red weathering pumice defining a eutaxitic foliation is present only near the base and top of the tuff (Fig. 19); elsewhere it apparently has been obliterated by welding and devitrification. The flattened pumice is usually 2-3 cm in length, although locally it is up to 20 cm long; the length to thickness ratio is approximately 4:1. Near section 7 (Fig. 3), a 10 m thick light green weathering uppermost zone contains up to 20% highly flattened white pumice. Angular lithic fragments (usually 5 mm, but up to 6 cm) are sparse (3%) and predominantly cognate (accessory). The tuff is mineralogically zoned, containing less than 1% clear fractured quartz microphenocrysts near the base, and a maximum of 3-4% quartz (less than 5 mm) and 1% potassium feldspar (1-3 cm) near the top.

In thin section, the tuff comprises highly fractured quartz and feldspar phenocrysts (Fig. 20). Some quartz crystals have highly embayed margins (Fig. 21) and the feldspars occur as corroded subhedral to anhedral crystals (Fig. 20). The moderately (Fig. 22) to densely (Fig. 21) welded vitroclastic matrix wraps around the phenocrysts, and is recrystallized to a dense assemblage of quartz, feldspar, sericite and iron oxides (hematite).

Figure 18. Rhyolite ash-flow tuff, Zebulon Formation, with coarse spherulitic zone near the base grading upward into a massive interior. Hammer is 35 cm long. GSC 204400-A.

Figure 19. Eutaxitic foliation in upper portion of rhyolite ash-flow tuff, Zebulon Formation. Note lithic fragment in centre of photo. Diameter of coin is 2 cm. GSC 204400-K.

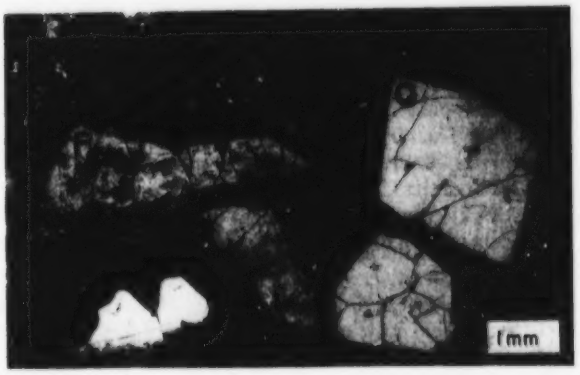

Figure 20. Phenocryst-rich upper part of rhyolite ash-flow tuff, Zebulon Formation. The fractures in the altered feldspar crystals (F) and quartz crystals (Q) are typical of this tuff.

Figure 21. Resorbed quartz crystals (Q) in rhyolite ash-flow tuff, Zebulon Formation. Densely welded matrix wraps around the phenocrysts.

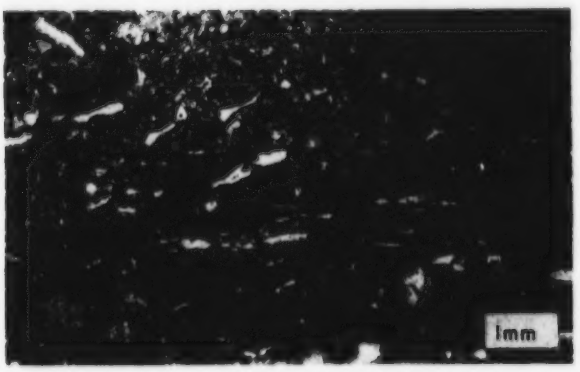

Figure 22. Vitroclastic texture in devitrified and oxidized matrix of welded rhyolite ash-flow tuff, Zebulon Formation.

A dark brown weathering, lithic-rich, densely welded (Fig. 23) dacite ash-flow tuff fills paleovalleys in the upper surface of the rhyolite ash-flow tuff. It is present only on central Bell Island where it is up to 60 m thick. Sparse (less than 1%) fractured quartz phenocrysts were the only phenocrysts observed. Accidental fragments of angular to rounded andesite (1-180 mm) account for up to one third of the rock. Highly flattened (20:1) orange and black pumice fragments reach a maximum of 30 cm in diameter.

Upper member

Rhyolite flow-domes and breccias characterize the upper member, which comprises six mappable units: four distinct units of rhyolite flow(s), a unit of mafic to intermediate lavas and a volcaniclastic unit. The upper member extends from Beaverlodge Lake to central Hottah Lake. Mineralogy and stratigraphic position distinguish the four rhyolite units, which outcrop on central Bell Island and on the mainland to the northeast of Bell Island. The mafic to intermediate lavas are a volumetrically less significant unit of the upper member and are petrographically and chemically identical to those of the lower member. They are intercalated with, and have the same regional distribution as the rhyolite flows. Massive rhyolite breccias and minor lithic sandstone characterize the volcaniclastic unit; exposures are best on central Bell Island, with minor occurrences on the mainland to the northeast of Bell Island. The lower boundary of the upper member corresponds to the top of the middle member, or, where this latter member is absent, the base of the stratigraphically lowest rhyolite flow.

The rhyolites range from aphyric to porphyritic. The most abundantly porphyritic flow occurs on central Bell Island (PZ-ur2, Fig. 2). It overlies either basalt (PZ-ub) or rhyolite breccia (PZ-uv) of the upper member; the basalt in turn overlies dacite ash-flow tuff (PZ-md) of the middle member. This same younging of middle to upper member occurs on the north side of the rhyolite flow, suggesting that the flow is either filling a primary topographic depression or occurs in the core of a fold. Bedding measurements are scarce and there is no way to further clarify the structural setting of the flow. The thickness of the flow is a maximum of 900 m, but is less if the flow is folded.

The flow is porphyritic and contains 8% clear quartz phenocrysts (2-3 mm) and 6% bladed to blocky potassium feldspar phenocrysts (up to 8 mm). At the base of the flow is a monolithologic flow breccia, which grades into the massive internal lava. The breccia contains amygdaloidal flow-layered quartz and potassium feldspar porphyritic blocks up to one metre across in a light green cryptofelsite matrix (Fig. 24). This flow was collected for U-Pb (zircon) dating.

Thin sections show fractured and embayed quartz anhedra, slightly rounded quartz bipyramids and potassium feldspar with embayed margins and incipient alteration to sericite and other unidentified minerals. The matrix is a cryptocrystalline intergrowth of quartz, feldspar and iron-titanium oxides. Finely disseminated hematite gives the flow a brick-red colour.

The close similarity between the mineralogy of this flow and the directly underlying rhyolite ash-flow tuff of the middle member, suggests that they may be comagmatic. Tapping more crystal-rich lower portions of the magma chamber with time could explain the crystal-rich nature of the flow versus tuff.

On northern Bell Island is a 200 m thick, light grey weathering, finely (millimetre-scale) flow-layered rhyolite (PZ-ur1, Fig. 2). It conformably overlies Beaverlodge Lake Sandstone, but its stratigraphic position with respect to the middle member is uncertain because the latter is absent in this locale. Dacite flow(s) of the upper member conformably overlie the rhyolite, but no other rhyolites of the upper member occur in this area, so that the exact stratigraphic position of PZ-ur1 within the upper member is unclear. This flow is unique to the study area in that its volcanic vent is well exposed. Intrusive to extrusive relationships are illustrated in Figure 25. Faulting bisects the vent and is responsible for an approximately 60 degree clockwise rotation of the northwestern half of the vent, but details on the style of

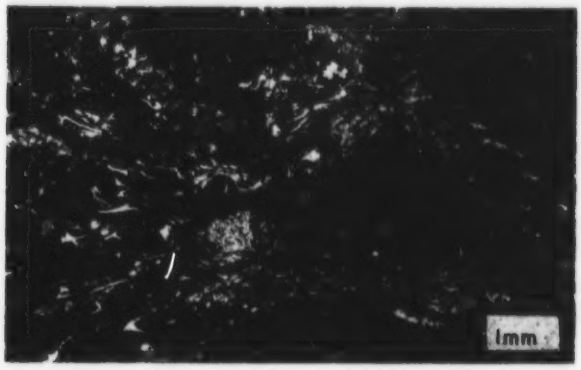

Figure 23. Lithic fragments in dacite ash-flow tuff, Zebulon Formation, surrounded by densely welded matrix. This lithic-rich tuff only occurs on Bell Island where it directly overlies the rhyolite ash-flow tuff.

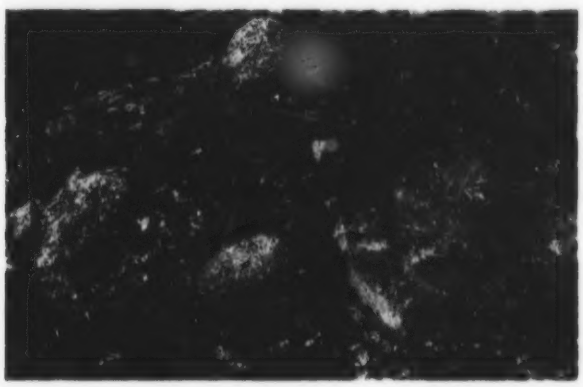

Figure 24. Rhyolite flow breccia, Zebulon Formation. Note pen (15 cm long) in upper right corner. GSC 204113-S.

faulting are unresolvable. An intrusive phase of the rhyolite crosscuts bedding of the Beaverlodge Lake Sandstone and disturbs bedding in the immediate vicinity of the contact. When the sandstone beds are restored to the horizontal, the intrusive contact is nearly vertical. Up section (to the northeast) the contact turns abruptly and the rhyolite conformably overlies Beaverlodge Lake Sandstone. In both the extrusive and intrusive rhyolite, prominent flow layers are parallel to the contact immediately adjacent to it, but are convoluted away from it. At the intrusive contact, there is a finely flow-layered marginal zone 8 cm wide, defined by alternating light green (formerly glassy) and white laminations. In sharp contact with the laminations is a 12 cm thick zone, containing abundant flattened quartz amygdules, that grades inward to a zone characterized by more fine flow layering.

At the base of the extrusive part of the flow, east of the volcanic neck, is a light pink to buff weathering basal flow breccia. It contains from 20-80% fragments (1-12 cm) identical in appearance to those in the rhyolite flow, in a light green matrix. Minor exotic basalt fragments are locally present. The contact with the overlying rhyolite (PZ-ur1) is gradational.

This flow is essentially aphyric with sparse (less than 1%) feldspar phenocrysts (1 mm). Identification of the type of feldspar(s) is hampered by intense alteration. Relict Carlsbad and minor albite twinning is present in several phenocrysts, indicating that at least some of them were plagioclase. The matrix is cryptocrystalline, finely flow layered (Fig. 26) and contains coarser microcrystalline lenses of quartz and feldspar. Perlitic fractures and spherulites (Fig. 26, 27) attest to the original glassy character of much of the flow.

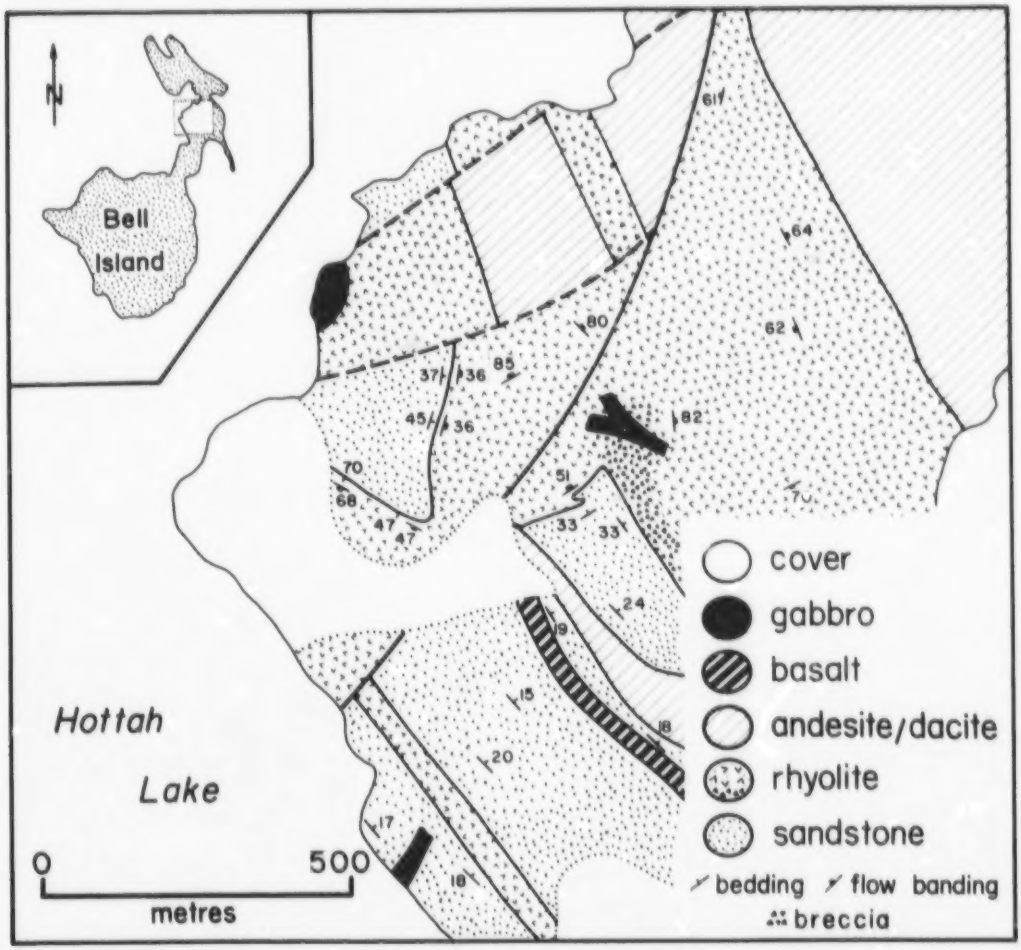

Figure 25. Geological map illustrating rhyolite vent on central Bell Island. Later faulting bisects the vent and has rotated the northwestern half approximately 60° in a clockwise direction.

Unit PZ-ur3 (Fig. 2) is a red weathering aphyric rhyolite flow that overlies unit PZ-ur2, with rhyolite breccia occurring along most of the contact. It outcrops on the mainland to the northeast of Bell Island and reaches a maximum thickness of 125 m. It is finely flow layered and microamygdaloidal. North along strike is a unit of nondifferentiated rhyolite flows (PZ-ur4, Fig. 2) that are distinguished from PZ-ur3 by the presence of minor quartz and potassium feldspar phenocrysts. These flows either directly overlie rhyolite ash-flow tuff of the middle member, or mafic to intermediate flows and rhyolite breccia of the upper member. The maximum thickness of the unit is about 125 m. Both PZ-ur3 and PZ-ur4 are characterized by devitrification and hydration textures, alteration and hematite staining similar to that already described.

Conjuror Bay Formation

Hildebrand (1982, 1984a,c) named the succession of sedimentary and pyroclastic rocks that outcrop in the Conjuror Bay area the Conjuror Bay Formation and divided it into a lower member of mature quartzarenite and an upper member comprising mudstone, tuff, sandstone and conglomerate. The formation overlies Hottah Terrane along an erosional unconformity and is in turn overlain by a thick sequence of pillow basalts. In the Hottah and Beaverlodge lakes areas a similar sequence of sedimentary rocks conformably overlies the Zebulon Formation. The top of the sedimentary sequence is not exposed around Beaverlodge Lake, but interfingers with overlying pillow basalts in the Hottah Lake area. Based on lithology and stratigraphic position, it is proposed that sedimentary rocks conformably overlying the Zebulon Formation in the Hottah and Beaverlodge lakes areas are similar to those described by Hildebrand (1984a) in Conjuror Bay and are therefore correlated with and included in the Conjuror Bay Formation.

Exposures of the Conjuror Bay Formation around Hottah Lake are relatively poor; the best occur in synclines to the east and northeast of Bell Island (Fig. 2). The formation also outcrops as thin discontinuous slivers along intrusive contacts with gabbro sills that occur as resistant ridges forming curvilinear islands in Hottah Lake (Fig. 2). It is likely that the less resistant formation occupies the more deeply eroded bays between sills. The estimated thickness of any one section is about 100-300 m (Fig. 3). Both the lower and upper members are present in the Hottah Lake area, although not in a continuously exposed section.

The lower member is only exposed on the mainland to the east of Bell Island. This area is structurally complex with tight folds cut by numerous faults of unknown displacement. In the core of a syncline, the lower member conformably overlies massive rhyolite breccia of the Zebulon Formation. On the western limb of the fold, it is in fault contact with Hottah Terrane and on the eastern limb it is stratigraphically above both a rhyolite flow (PZ-ur4) and rhyolite ash-flow tuff (PZ-mr) of the Zebulon Formation, but the contacts are not exposed. At the base of the lower member is a clast-supported volcanic conglomerate with dark red rounded boulders up to 0.3 m in diameter. The conglomerate grades upward into well-bedded granular arkose interbedded with mudstone and siltstone. Beds range from laminations to 10 cm in thickness. Asymmetrical and symmetrical ripples are well developed. Mature quartzarenite is intercalated with and overlies the arkose. It is white to pink weathering, well bedded and medium to fine grained. Beds are lenticular and range from 2-3 cm to 1 m in thickness, with laminations rich in heavy minerals which accentuate trough cross-bedding. Lenses of subrounded vein quartz pebbles occur locally.

The upper member contains siltstone, concretionary mudstone, chert, tuff and fine grained quartzarenite. Best exposures are on the mainland to the northeast of Bell Island. This member is well stratified and predominantly planar bedded with continuous 1-15 cm layers (Fig. 28). Individual strata are internally well bedded to thinly laminated. Less resistant beds weather recessively. Low angle cross-bedding, climbing ripples and sinuous asymmetrical ripples are present locally. Many beds show evidence of soft-sediment defor-

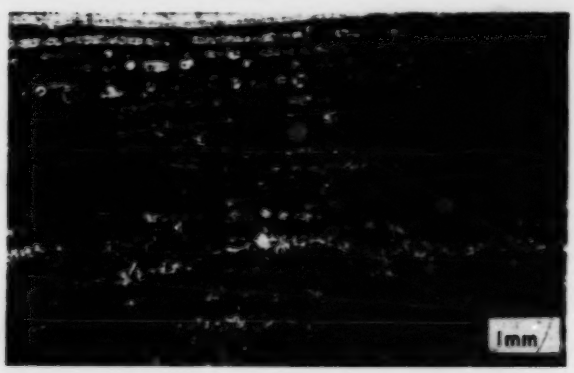

Figure 26. Finely flow-layered and spherulitic rhyolite flow, Zebulon Formation.

Figure 27. Spherulitic zone at the base of a rhyolite flow, Zebulon Formation. Diameter of coin is 2 cm. GSC 204400-J.

mation such as mud rip-ups, ball-and-pillow structures, slump folds, boudinaged layers and contorted bedding. Sedimentary rocks are metamorphosed to the albite-epidote hornfels facies of Turner (1968) at contacts with gabbro sills.

In the Hottah Lake area, the maturity and overall fining-upward nature of the sequence, the presence of ripple stratification and the upward transition from trough cross-stratification to parallel lamination, suggest a beach-to-offshore transgressive sequence (cf. McCubbin, 1982 and Reinson, 1984). This concurs with Hildebrand's (1984a) interpretation of the Conjuror Bay Formation to the north as being marginal marine. In addition, the conformable relationship between the Conjuror Bay Formation and the overlying pillow basalt sequence supports a subaqueous depositional environment, at least for the upper part of the Conjuror Bay Formation.

Figure 28. Planar-bedded siltstones and sandstones in the upper member of the Conjuror Bay Formation (on mainland to the northeast of Bell Island). Dark, less resistant beds weather recessively and accentuate bedding. Note pen (15 cm long) in upper right corner. GSC 204400-I.

Bloom Basalt

Two to three kilometres of pillow basalt, associated breccia and tuff and intercalated oolitic and stromatolitic dolomite overlie the Conjuror Bay Formation in the Conjuror Bay area (Bloom Basalt of Hildebrand, 1982, 1984a,c). In the vicinity of Hottah Lake, one to two kilometres of pillow basalt, pillow breccia, hyalotuff, sedimentary rocks and a dacite flow overlie the Conjuror Bay Formation. Locally, such as on the mainland to the northeast of Bell Island (Fig. 2), the Conjuror Bay Formation is absent and the pillow basalt sequence lies directly on the Zebulon Formation. Based on similarities in lithology and stratigraphic position, it is proposed that the pillow basalt assemblage in the Hottah Lake area be included in Bloom Basalt, a correlation first suggested by Hoffman and McGlynn (1977). Thus, the formation has a lateral extent of 45 km when separation along the transcurrent faults is restored (Fig. 3). The top of the sequence is not exposed in the Hottah Lake area because younger Great Bear plutons intrude it; therefore, its original thickness is unknown.

The lower contact between Bloom Basalt and the Conjuror Bay Formation is irregular, with bits of sediment squeezed up between basal pillows. Massive monolithologic pillow breccias are common near the contacts and elsewhere in the pillow pile. Light green, fine grained, poorly bedded hyalotuff horizons as well as discontinuous mudstone and fine grained sandstone beds occur within the pillow basalt sequence on islands to the northeast of Bell Island. Although shoreline exposures of the pillows are excellent, the overall exposure of Bloom Basalt is not sufficient to determine whether the lavas were erupted from fissures or central vents. Randomly distributed amygdules, cavernous cores with pillow shelves (Fig. 29) and amygdules radiating inward from the selvages (Fig. 30) are abundant. The texture of the pillows varies considerably from nearly aphyric to abundantly plagioclase porphyritic. Plagioclase phenocrysts occur as discrete megacrysts or in glomeroporphyritic aggregates of two to five plagioclase crystals. Amygdules and phenocrysts occur both internally and in the chilled selvages (Fig. 31).

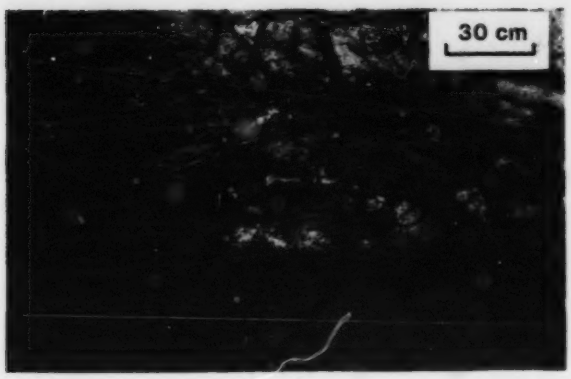

Figure 29. "Triple decker" shelves in pillow lava (15 cm long pen, photo centre), Bloom Basalt. Bedding plane is nearly perpendicular to photo. GSC 204113-W.

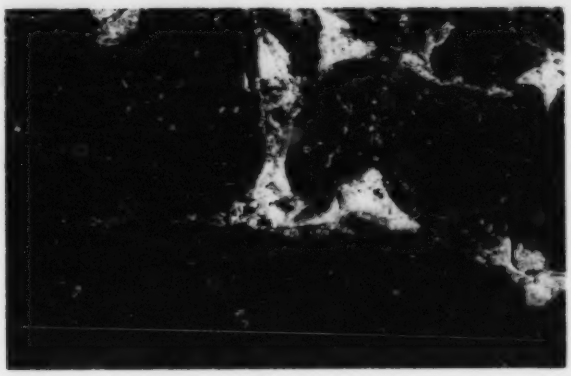

Figure 30. Radiating amygdules in the outer margins of pillows, Bloom Basalt. Pen is 15 cm long. GSC 204113-Y.

The basalts contain plagioclase, clinopyroxene and iron-titanium oxides. Olivine has not been observed. Primary textures are well preserved, except near the margins of younger Great Bear plutons where the pillows have been flattened. Many pillows have striking quench textures with acicular swallow-tailed plagioclase set in a matrix of altered glass (Fig. 32). Others are holocrystalline, ophitic to subophitic intergrowths of euhedral plagioclase laths and poikilitic clinopyroxene crystals. Iron-titanium oxides occur as anhedral interstitial grains and show exsolution lamellae. The glomeroporphyritic rocks contain euhedral to subhedral plagioclase crystals of different size, shape and orientation, in clusters generally less than 4 cm, in hypocrystalline to holocrystalline matrixes. Alteration is variable: in some samples the groundmass plagioclase is relatively free of alteration and clinopyroxene is entirely altered to uralite and/or chlorite; in others, the clinopyroxene is relatively fresh and the groundmass plagioclase is highly altered to saussurite and sericite. Plagioclase occurring as megacrysts and glomerocrysts is nearly completely saussuritized.

Pillowed flows are unanimously accepted as products of either subaqueous eruptions, or the flow of lava into water. Subaerial eruption for at least some of Bloom Basalt cannot be ruled out because vents are not exposed. However, based on the thickness and lateral extent of the pillowed flows, and the lack of any heterogeneous rounded epiclastic fragments suggesting subaerial erosion, the pillows are interpreted to have formed by subaqueous eruption. The subaerial to subaqueous transition between eruption of lavas of the Zebulon Formation and those of Bloom Basalt implies eruption of the basalt during, or closely following, subsidence. Oolitic and stromatolitic patch reefs intercalated at various horizons with the pillowed flows in the Conjuror Bay area (Hildebrand, 1984a,c) indicate that water depths remained shallow throughout the eruption of the 2 km of pillow basalts and that the eruption of Bloom Basalt kept pace with subsidence. The highly amygdaloidal nature of the pillow basalt implies water depths less than about 500 m (Moore, 1965, 1970; Moore and Schilling, 1973). Identification of the stromatolite *Jacutophyton* (see Hildebrand, 1984a), known only from environments interpreted as marine, taken together with observations that the basalt is pillowed, amygdaloidal and intercalated with oolitic shoals, indicates a shallow marine depositional environment for Bloom Basalt.

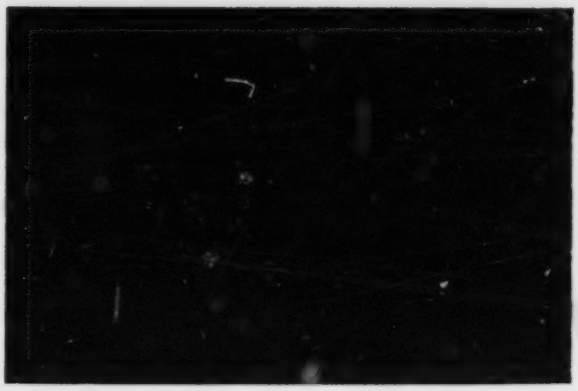

Figure 31. Plagioclase megacrystic and glomerocrystic pillow lava, Bloom Basalt. Note phenocrysts in the chilled selvages. Pen is 15 cm long. GSC 203695-T.

Dacite member

The stratigraphically highest unit exposed in the Bell Island Bay Group, and included within Bloom Basalt, is a flow-layered, potassium feldspar, plagioclase and quartz porphyritic dacite flow with local brecciated zones (section 4, Fig. 3). Exposures are limited to several islands about 7 km north of Bell Island. The flow occurs in the core of a syncline, the exposed thickness is 125 m and the lateral extent is 2-3 km along strike. A Fishtrap Lake Gabbro sill (see following section) intrudes the flow, but no stratigraphic contacts were observed. Stratigraphic position is based on the occurrence of pillow basalts in the immediate vicinity, and relative location with respect to other units after separation along the transcurrent faults is restored.

Fishtrap Lake Gabbro

The name Fishtrap Lake Gabbro is proposed here for gabbroic dykes and sills that intrude all units of the Bell Island Bay Group and outcrop from Beaverlodge Lake to Conjuror Bay (PF, Fig. 2). The gabbros consistently occur as north-trending dykes in the Hottah basement (Fig. 33), oblique sheets in lower units of the Bell Island Bay Group and sills (Fig. 34) in the Conjuror Bay Formation and Bloom Basalt. The gabbro sills and Bloom Basalt are overlain with angular unconformity by Moose Bay Tuff in the Conjuror Bay area (Hildebrand, 1982, 1984a). The maximum aggregate thickness of gabbro sills is about equal in thickness (1-2 km) to Bloom

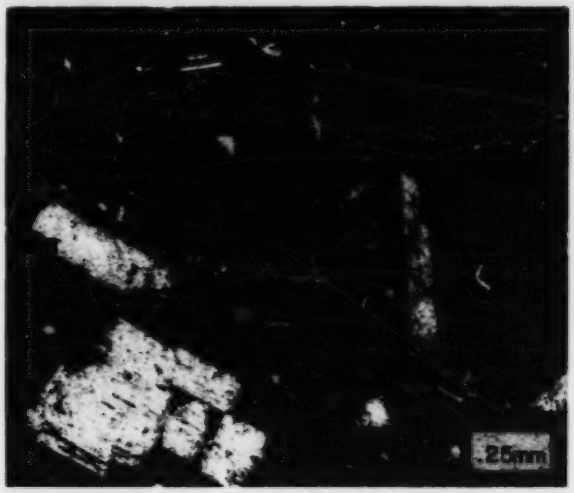

Figure 32. Photomicrograph of pillow basalt, Bloom Basalt, showing two generations of plagioclase crystals: large euhedral megacrysts and acicular swallow-tailed quench crystals, surrounded by a cryptocrystalline matrix.

Basalt, although considerable variations occur along strike. The intrusions are the youngest rock unit included in the Bell Island Bay Group.

The gabbros are fine grained diabasic to coarse grained equigranular rocks varying from aphyric to plagioclase porphyritic. As in Bloom Basalt, plagioclase occurs as discrete megacrysts or as glomerocrysts typically 1-2 cm in diameter (Fig. 35), although 10 cm size clots are not uncommon, and a few clusters are up to 20 cm in diameter. For the most part, the plagioclase clots are randomly distributed throughout the sills, although in one location on an island in northeastern Hottah Lake the sills have spectacular alternating phenocryst-rich and phenocryst-poor layers (Fig. 36). The genesis of the layering is unclear. One of the largest sills that outcrops on numerous small islands northeast of Bell Island is zoned. A basal pyroxene poikilitic zone of this sill (Fig. 37) grades up into a plagioclase glomerocrystic interior zone (Fig. 35) with discontinuous pegmatite zones that contain pyroxene needles up to 8 cm long toward the top (Fig. 38). The uppermost part of the sill is a fine grained nonporphyritic diabasic border zone containing calcite and quartz amygdules to 10 cm (Fig. 39).

A glomeroporphyritic gabbro similar to Fishtrap Lake Gabbro occurs as a 500 m thick intrusion in the Akaitcho Group, 120 km to the east (Easton, 1981). These gabbros are similar to the "leopard rocks" in the Labrador Trough (Baragar, 1967) and gabbroic sills in the Sleeper Islands (Cadieux, 1980), and texturally resemble sills from the

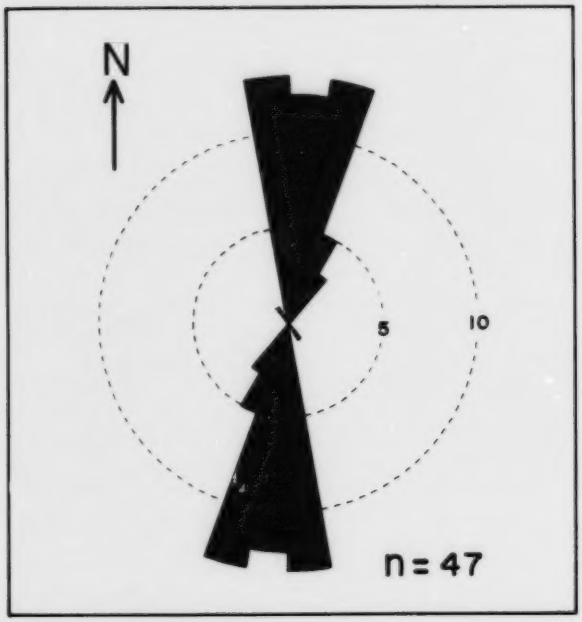

Figure 33. Rose diagram representing the trend of 47 Fishtrap Lake Gabbro dykes intrusive to Hottah Terrane. The north trend of the dykes indicates east-west extension during basaltic volcanism.

Figure 35. Plagioclase glomerocrystic texture typical of many sills and dykes of Fishtrap Lake Gabbro. Pen is 15 cm long. GSC 204113-F.

Figure 34. Columnar jointed, nearly flat lying gabbro sill, Fishtrap Lake Gabbro, north of Bell Island. Cliff is about 20 m high. GSC 204400-G.

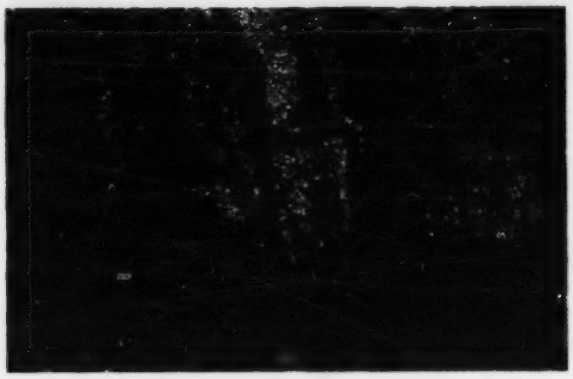

Figure 36. Alternating plagioclase-rich and plagioclase-poor layers in gabbro sill, Fishtrap Lake Gabbro, northern Hottah Lake. Pen is 15 cm long. GSC 204400-C.

Figure 37. Photomicrograph of poikilitic pyroxene near the base of a weakly zoned sill, Fishtrap Lake Gabbro.

Figure 38. Pegmatitic zone containing radiating acicular pyroxene crystals, upper part of zoned gabbro sill, Fishtrap Lake Gabbro. Diameter of coin is 2 cm. GSC 204113-V.

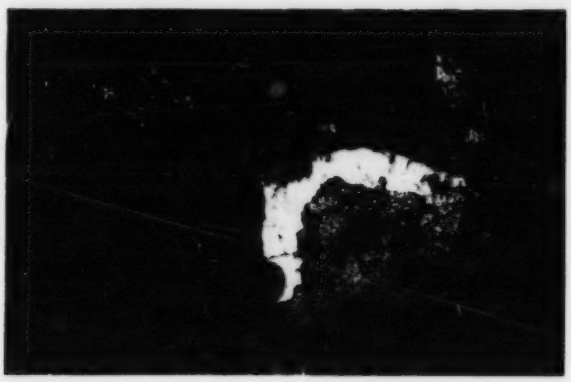

Figure 39. Large quartz-filled amygdule in upper portion of zoned gabbro sill, Fishtrap Lake Gabbro. Diameter of coin is 2 cm. GSC 204400-D.

Proterozoic Gardar alkali intrusions in south Greenland (Bridgwater and Harry, 1968). Cullen et al. (1985) describe similar plagioclase ultraphyric basalts from the Galapagos Archipelago which they have termed abingdonites.

Mineralogically, petrographically and texturally the gabbros are identical to the basalts they intrude except for their coarser grain size. They contain euhedral plagioclase laths, poikilitic clinopyroxene (Fig. 37) and interstitial iron-titanium oxides. Alteration is highly variable as in the pillow basalts. The partly to completely saussuritized glomerocrysts are commonly surrounded by nearly continuous 1-3 mm rims of unaltered feldspar. In both the pillow basalt and the gabbro, the anorthite (An) content of the interior of a typical megacryst (based on microprobe work by D. Morrison at Johnson Space Center, 1986) is An86. The anorthite content of the thin unaltered rims averages An63 which is consistent, in general, with the matrix plagioclase. The calcic cores of the megacrysts are comparable to the plagioclase composition of many Archean rocks (D. Morrison, pers. comm., 1986) and of plagioclase phyric mid-ocean ridge basalts (Stakes et al., 1984).

Bloom Basalt and Fishtrap Lake Gabbro are interpreted to be comagmatic based on their identical distinctive glomeroporphyritic textures and similar whole rock chemistry. The presence of plagioclase megacrysts and glomerocrysts in the chilled selvages of pillows and border zones of sills indicates that the phenocrysts did not form in situ, but crystallized elsewhere and were transported to the site of emplacement. However, whether they crystallized from the same parental melt as the host rock or are xenocrystic in nature is unknown. The megacrysts/glomerocrysts are clearly in disequilibrium with the host melt as evidenced by both the significantly more sodic rims and the gap in anorthite content between cores and groundmass plagioclase crystals. Slow crystallization under different pressure-temperature conditions would result in unzoned megacrysts and glomerocrysts of a different composition from late forming rims and groundmass plagioclase. This may partially explain the occurrence of fresh plagioclase groundmass crystals in the same rock as the saussuritized megacrysts and glomerocrysts, because the two are of composition dissimilar enough to have different susceptibilities to subsequent alteration. Alternatively, the calcic cores may be xenocrystic and altered prior to incorporation within the host melt.

As a tentative conclusion, the clusters of plagioclase phenocrysts in both the pillow basalts and gabbro sills are regarded as products of early crystallization of the same magma that gave rise to the host rock. The occurrence of both aphyric and porphyritic sills and pillowed flows at all stratigraphic horizons suggests a complex magmatic plumbing system, possibly involving alternate tapping of individual magma chambers at various stages of crystallization or tapping different horizons of a single chemically stratified magma chamber. The gabbro sills, which are more abundant and somewhat thicker where they intrude the Conjuror Bay Formation, may have been high-level magma chambers which fed upper parts of Bloom Basalt.

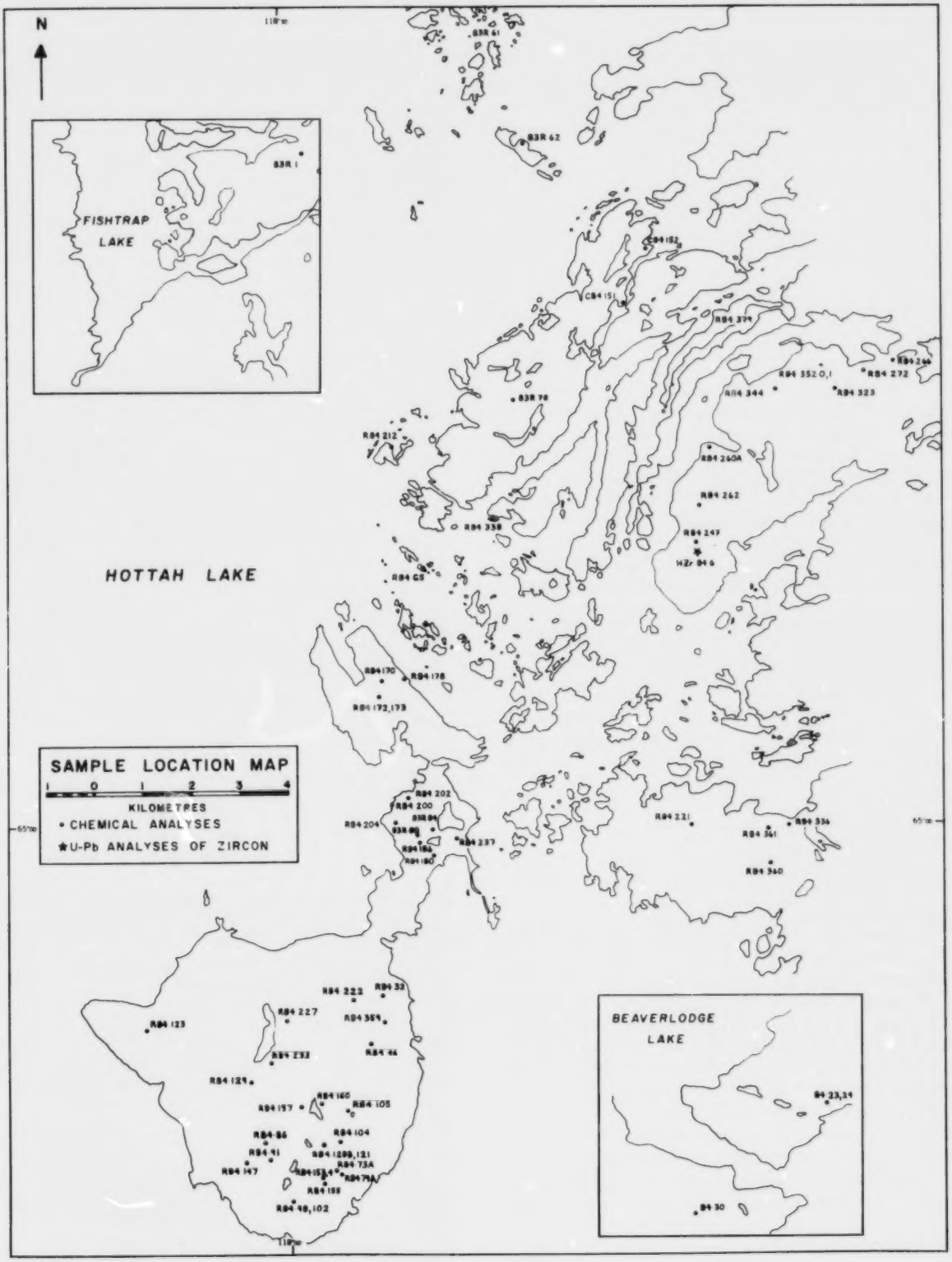

Figure 40. Sample location map. See Figure 1 for index map. See Appendix for the geochemistry of the indicated samples.

U-PB (ZIRCON) AGE

U-Pb (zircon) data (Bowring and Van Schmus, 1982; Bowring, 1984, 1985), based on 15 years of geological mapping, provide constraints for some of the magmatic and tectonic activities during the development of the Wopmay Orogen. However, there are questions regarding the exact age, regional significance and tectonic setting of the Bell Island Bay Group. To aid in clarifying these points, a porphyritic rhyolite flow (PZ-ur2, Fig. 2) of the Zebulon Formation was collected for U-Pb (zircon) dating. Figure 40 shows the sampling location (sample HZr-84-6).

Analytical Methods

U-Pb (zircon) work was done at the Geochronology Laboratory of the Geological Survey of Canada, Ottawa. Zircons were separated from crushed rock samples using standard heavy liquid techniques, were split into six size fractions and were further subdivided using a Frantz isodynamic magnetic separator. The least magnetic portions of the varying size fractions were hand picked by the author in order to obtain the clearest, least fractured, inclusion-free euhedral zircons for analysis. These zircons were abraded to remove the surface regions which are most susceptible to chemical alteration and Pb loss (Krogh, 1982). Zircons were dissolved and Pb and U separated using procedures modified from Krogh (1973). Concentration data were obtained using a mixed $^{205}Pb/^{235}U$ or a mixed ^{205}Pb-^{238}U-^{235}U tracer. Isotopic ratios were measured on a Finnigan-MAT 261 mass spectrometer equipped with a fully adjustable multiple collector and electron multiplier using a data collection procedure outlined by Roddick et al. (1987). Data points were evaluated by means of a modified York (1969) regression as outlined in Parrish and Van Breeman (1985). Errors on ages are quoted at the 95% confidence level.

Results

Zircons separated for analysis were colourless or pale yellow and euhedral to stubby (length:width = 3:1) and contained no visible relict cores (Fig. 41, 42). Analytical data are presented in Table 2. The six data points are discordant, but define a linear array on a concordia diagram that intersects the concordia curve at 1898.4 +7.2/-6.3 Ma (Fig. 43). The $^{207}Pb/^{206}Pb$ intercept age is interpreted to reflect the time of extrusion and quenching of the flow. No geological significance is attributed to the lower intercept at 0 Ma. The discordant age pattern can be attributed to either inherited zircons or to Pb loss. Because the zircons analyzed contain no visible relict cores, Pb loss is more likely. However, whether an episodic, continuous or dilatancy model applies is not critical to the accurate interpretation of the primary age and is beyond the scope of this report.

Discussion

Rocks of the Bell Island Bay Group have previously been considered to be the oldest supracrustal rocks of the McTavish Supergroup and have been included within the Great Bear Magmatic Zone (Hoffman and McGlynn, 1977; Hildebrand, 1981; Hildebrand et al., 1983, 1984; Hildebrand and Roots, 1985; Reichenbach, 1985a). The Great Bear Magmatic Zone comprises all supracrustal and intrusive rocks of western Wopmay Orogen that postdate the deformation of Coronation Margin during the Calderian Orogeny (R.S. Hildebrand, pers. comm., 1986), which is bracketed between 1900 Ma and 1880 Ma (Bowring, 1985). Because rocks of the Bell Island Bay Group, themselves little deformed, overlie penetratively deformed rocks of Hottah Terrane, the deformation of which has been interpreted to be synchronous with the Calderian Orogeny (Hildebrand et al., 1983; Hoffman and Bowring, 1984; Hildebrand and Roots, 1985), they were

Figure 41. Abraded zircon crystals, -105/+74 size fraction, analyzed for U-Pb composition.

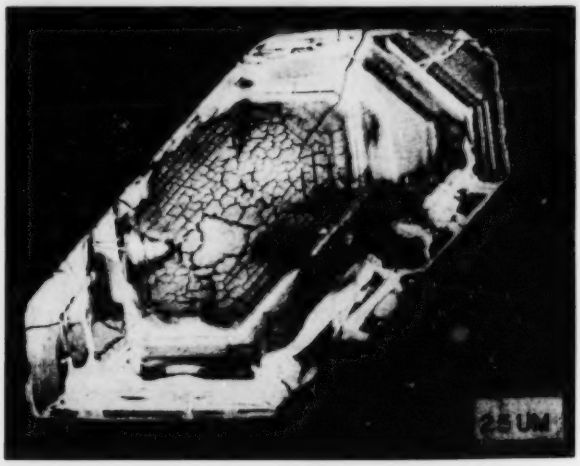

Figure 42. Etched euhedral zircon crystal displaying oscillatory igneous zoning. Note the lack of any inherited core.

Table 2. U-Pb analytical data

Sample Fraction*	wt (mg)	U (ppm)	Pb* (ppm)	Measured $^{206}Pb/^{204}Pb$	Mole % $^{208}Pb^*$	Isotopic Compositions $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Isotopic Age $^{207}Pb/^{206}Pb$
-105 + 74	0.032	527.1	186.7	3343	0.111	0.3276	5.254	0.1163	1900.3
-105 + 74	0.011	200.7	68.39	1020	0.116	0.3136	5.032	0.1164	1901.3
-149 + 105	0.079	417.3	73.74	5604	0.110	0.3060	4.895	0.1160	1896.0
-149 + 105	0.047	340.3	107.6	4881	0.115	0.2915	4.676	0.1163	1900.8
-149 + 105	0.080	326.4	107.8	3942	0.109	0.3065	4.913	0.1163	1899.3
-105 + 74	0.086	333.9	113.2	7505	0.109	0.3145	5.029	0.1160	1895.1

* Numbers refer to the size of zircons in microns; all samples are abraded using the method of Krogh (1982).

*Pb = radiogenic Pb content.

Blanks associated with these analyses were approximately 35 picograms Pb, 50 picograms U.

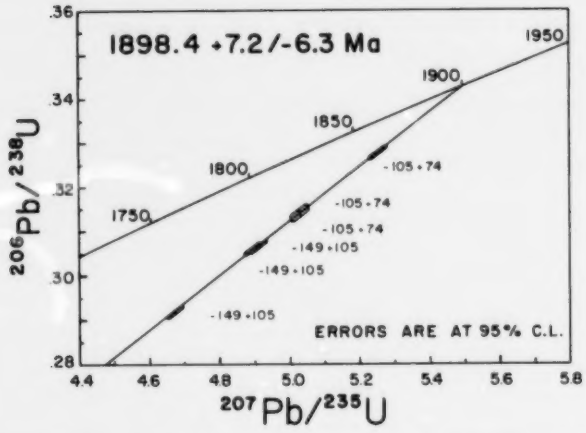

Figure 43. U-Pb concordia plot for zircon analyses from a rhyolite flow of the Zebulon Formation. The 207Pb/206Pb intercept age is interpreted to reflect the time of extrusion and quenching of the flow.

previously considered to postdate the deformation of the Coronation Supergroup. Several implications, therefore arise from this data.

1. Rocks of the Zebulon Formation (Bell Island Bay Group) predate the Calderian Orogeny and therefore should not be included within the Great Bear Magmatic Zone; it is proposed to remove the Bell Island Bay Group from the Great Bear zone and consider them, instead, as cover rocks to Hottah Terrane.

2. The fact that rocks of the Zebulon Formation predate the Calderian Orogeny, are not penetratively deformed, yet unconformably overlie penetratively strained rocks of Hottah Terrane, necessitates that the main deformation in Hottah Terrane is pre-Calderian in age, and therefore of unknown origin. The deformation of Hottah Terrane is likely due to a complex history of heterogeneous strain, which may in part, but certainly not in entirety, be due to the Calderian Orogeny.

3. Present age constraints indicate that a maximum of 25 Ma elapsed between deposition of the Bell Island Bay Group (1898 Ma) and the LaBine Group (1875 Ma, Bowring, 1985). This suggests that the locally exposed angular unconformity between Bloom Basalt (Bell Island Group) and the overlying LaBine Group may represent a greater time gap than was previously suspected and thus an unconformity of regional importance. Dating the dacite member which occurs at the top of Bloom Basalt could confirm this fact.

4. The ca. 1898 Ma age suggests a correlation among Bloom Basalt, Fishtrap Lake Gabbro and rocks of the Akaitcho and Grant groups to the east, based on similarities in age, composition and lithology.

STRUCTURAL GEOLOGY

Rigorous structural interpretations and reconstructions for the Bell Island Bay Group are severely limited due to a lack of kinematic indicators and piercing points, unknown fault plane orientations and the reactivation of pre-existing structures. The oldest deformational structures recognized are broad gently north-plunging folds with minor subsidiary folds on their limbs. Similar folding has affected most rocks of the Great Bear Magmatic Zone, although to the north and northeast of Hottah Lake the regional trend of the fold axes is northwesterly. This suggests that the folds of the Bell Island Bay Group could be due to a deformation that predates the Great Bear Magmatic Zone such as the Calderian Orogeny, but there is no way to test this possibility. Strain fabric attributable to the folding, recognized only in bedded tuff, is a low-angle cleavage that forms an angle of 30-40 degrees with the bedding plane and is steeper than bedding on both fold limbs.

These folds, and all the supracrustal rocks of the Great Bear Magmatic Zone, are segmented by right-lateral northeast-trending transcurrent faults. The faults are typical of those throughout Wopmay Orogen that have been interpreted as the result of east-west compression (Hoffman, 1980b; Tirrul, 1984). The faults, however, are not related to the folds, because different strain regimes are necessary to explain their nearly perpendicular respective orientations

(Anderson, 1951; Wilcox et al., 1973). A fabric possibly attributable to the east-west compression is a nearly vertical north-trending cleavage that is well developed in the bedded tuff unit of the lower member.

Brittle faults of easterly and northerly orientation affect virtually all the rocks of the Bell Island Bay Group. For instance, in areas of good stratigraphic control, east-trending faults having small amounts of displacement are prevalent (Fig. 44). For the most part, dips of the fault planes could not be measured. These faults must postdate folding, because many of them cut fold axes. The faults could be interpreted as subsidiary strike-slip faults associated with the major transcurrent movements. However, assuming strike-slip displacement, the offset is both sinistral and dextral, which is incompatible with the dextral displacement along the transcurrent faults. A more reasonable interpretation is that they are normal faults, formed perpendicular to the north-south extension direction during transcurrent faulting.

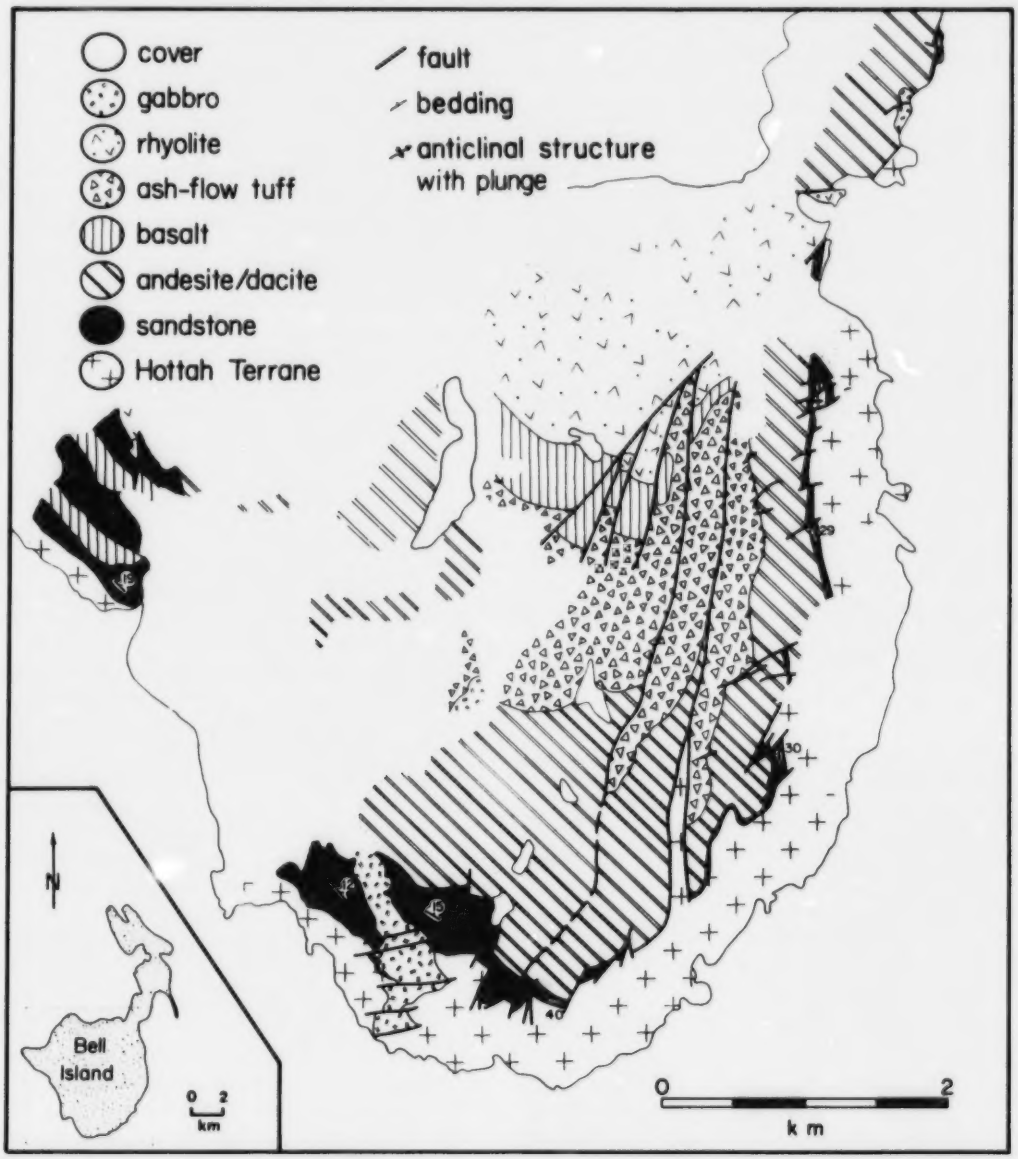

Figure 44. Simplified map of southern Bell Island illustrating faults.

Other faults trending north-northeast, with locally developed steep north-trending cleavages along their traces, terminate at an oblique angle to a minor transcurrent fault cutting Bell Island (Fig. 44). Relative offset between the faults cannot be accounted for by dextral strike-slip movement alone. One north-trending fault brings Hottah basement over rocks of the Zebulon Formation, and may be a reverse or thrust fault. One explanation for these faults is that they are earlier structures truncated by the transcurrent fault. A comparable thrust(?) fault is recognized to the northeast, on the other side of the transcurrent fault, where the ash-flow tuff member is repeated (Fig. 2). An alternative explanation is that both the transcurrent faults and the faults at an oblique angle to them are synchronous. An estimate of the strike-slip separation along the transcurrent fault ranges from one kilometre in the northeast to close to zero in the southwest. Thus, one model might be that these faults are due to the termination of the transcurrent fault by splaying. The compressional structures (cleavages, reverse faults) of the secondary faults are compatible with this model, according to which the faults occur in an area of compression (cf. Chinnery, 1961). However, left-stepping dextral strike-slip faults also produce compression in the step-over area (Rodgers, 1980; Segall and Pollard, 1980). Unfortunately, there is neither exposure to the south of Bell Island, nor aeromagnetic data, where the left-stepping transcurrent fault would likely continue.

Many of the transcurrent faults that cut rocks of the Bell Island Bay Group have a component of dip-slip movement. Perhaps this is a result of reactivation during a period of normal faulting, which is recognized in rocks of the younger Hornby Bay Group (Hoffman and McGlynn, 1977; McGrath and Hildebrand, 1984).

No structures have been recognized as clearly synvolcanic. However, Figure 3 illustrates that the Zebulon Formation is restricted to the southern extent of the Bell Island Bay Group, in contrast to the overlying Bloom Basalt, which extends as far north as Conjuror Bay. A possible interpretation is that the subaerial lavas were erupted in local fault-bounded areas of subsidence. Synvolcanic subsidence is clearly substantiated by the overlying thick pile of pillow basalts which necessitate extension, perhaps with associated normal faulting, during their eruption; therefore, subsidence could have begun during early subaerial volcanism and culminated during, or shortly after, extrusion of the thick pillow basalt pile. Any synvolcanic structures have likely been reactivated during later episodes of deformation and their origin obscured.

WHOLE-ROCK CHEMISTRY

Volcanic rocks of the Bell Island Bay Group were subdivided based on field data alone into two distinct stratigraphically conformable sequences: 1) a heterogeneous subaerial sequence (Zebulon Formation); and 2) a homogeneous subaqueous sequence (Bloom Basalt). The two formations have major differences in chemistry, a distinction which is critical to their tectonic interpretation.

Table 3. Analytical methods

	AA	XRF	ICP	other	Sample Number			
SiO_2, TiO_2, Al_2O_3, MgO, Fe_2O_3(T), MnO, CaO, K_2O, P_2O_5		X				R84-86	R84-153	R84-173
						R84-91	R84-154	R84-180
					83R-61	R84-98	R84-155	R84-186
					83R-68	R84-102	R84-157	R84-200
Na_2O	X				83R-78	R84-104	R84-160	R84-202
					83R-80	R84-105		R84-204
Ba		X			R84-73A	R84-129	R84-170	R84-235
					R84-81	R84-131	R84-172	R84-247
SiO_2, TiO_2, Al_2O_3, MgO, Fe_2O_3(T), MnO, CaO, K_2O, Na_2O, P_2O_5			X		83R-1	R84-32	R84-227	R84-344
					83R-62	R84-46	R84-233	R84-3520
					83R-84	R84-79A	R84-237	R84-3521
					R84-23	R84-120B	R84-260A	R84-359
					R84-24	R84-121	R84-262	R84-360
					R84-30	R84-147	R84-266	R84-361
					R84-31	R84-151	R84-272	R84-370
					C84-151	R84-178	R84-323	R84-379
Ba			X		C84-152	R84-212	R84-336	R84-388
					R84-23	R84-222	R84-338	R84-G5
FeO, H_2O,CO_2				X	all samples			
Ni, V, Yb, Zn			X		all samples			
Nb, Rb, Sr, Y, Zr		X			all samples			

AA = Atomic absorption spectroscopy;
XRF = X-ray fluorescence spectroscopy;
ICP = induced-couple plasma emission spectrometry

Analytical methods

Major oxide and trace element analyses were done at the Geological Survey of Canada by standard X-ray fluorescence, ICP-emission spectrometry and atomic absorption techniques (Table 3)--except for FeO (titration), H_2O (infrared detector) and CO_2 (infrared detector). Fe_2O_3 was calculated using Fe_2O_3(T) (XRF or ICP) - 1.11134 FeO (volumetric). Major and trace element analyses are listed in the Appendix; for sample locations see Figure 40. In the diagrams and discussion that follow, all analyses have been recalculated to 100% on a volatile-free basis.

Alteration

Volcanic rocks are notorious for their susceptibility to alteration. The main reason for this is the well-known metastable nature of volcanic glass (Morey, 1954). Not surprisingly, all of the rocks sampled for analysis have undergone some degree of alteration with the consequent development of low-grade mineral assemblages. The type of alteration is, of course, determined by the original composition of the rock; variations in degree and style of alteration therefore occur both within and among the Zebulon Formation, Bloom Basalt and Fishtrap Lake Gabbro.

Basalts and andesites of the Zebulon Formation have high and variable Fe_2O_3/FeO ratios (0.33-2.77%) and H_2O contents (0.70-3.70%) which are characteristic of hydrated and oxidized phases. High CO_2 contents (0.20-5.50%) are attributed to the alteration of ferromagnesian minerals to carbonate, evident in thin section. For the dacite-rhyolite range, H_2O contents (0.30-2.60%) are variable and CO_2 contents (0.00-0.40%) low. Fe_2O_3/FeO ratios reach a peak in the dacites (2.69-23.00), decreasing in the rhyolites (0.50-14.67) as total iron content also decreases.

The most striking alteration involves a sharp increase in K_2O and a decrease in Na_2O in rocks containing greater than 63% SiO_2 (Fig. 45). Some samples contain greater than 12% K_2O and less than 0.30% Na_2O. Other chemical changes accompanying the K_2O increase are dramatic increases in Rb

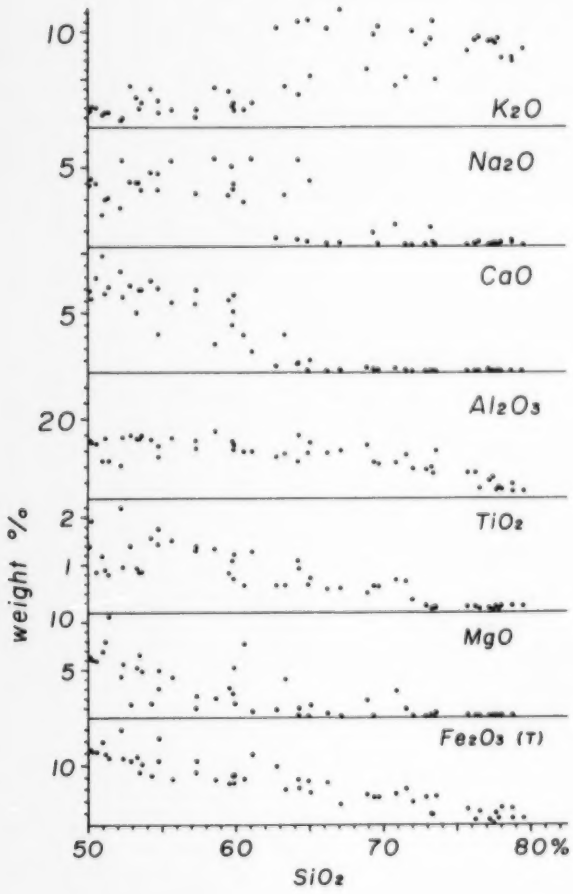

Figure 45. Harker variation diagrams (weight percent) for rocks from the Zebulon Formation. Note the presence of a continuous compositional suite from basalt to rhyolite. Sharp changes in contents of many oxides at 63% SiO_2 are due to alteration (Fig. 46). Total iron as Fe_2O_3.

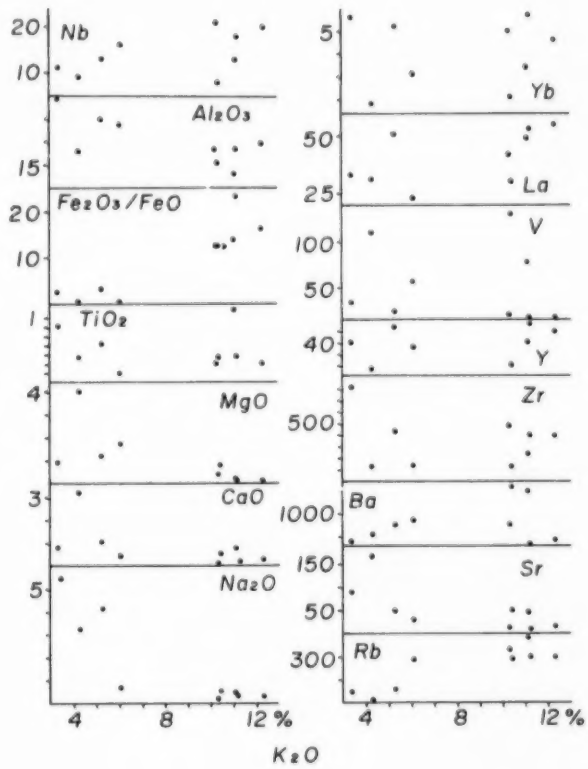

Figure 46. Selected major and trace elements plotted against K2O for samples with SiO_2 at 62%, in order to compare altered and nonaltered samples standardized with respect to silica. A sharp increase in K2O is accompanied by increases in Rb and Fe_2O_3/FeO and decreases in Na_2O, MgO and Al_2O_3. Other major, trace and rare earth elements are not systematically affected.

and Fe_2O_3/FeO, and variable decreases in MgO and Al_2O_3 (Fig. 46). Other major, trace and rare earth elements are not systematically affected. Similar alteration has been noted in Tertiary rhyolites from the Datil-Mogollon volcanic province in New Mexico, where potassium-enriched rhyolite contains 6-11.5% K_2O, compared to about 4-5% K_2O in the unaltered rock (Chapin et al., 1978; Chapin and Lindley, 1986). Numerous other workers have also documented K_2O metasomatism in volcanic rocks (e.g. Lipman, 1965; Keith et al., 1978; Gust et al., 1985). Of particular interest, seafloor rhyolites studied by Munha et al. (1980) are enriched in potassium and have potassium feldspar + hematite + quartz + illite-montmorillonite alteration assemblages. Along the same line, Sheppard and Gude (1968) documented rhyolitic tuffs altered progressively from glass to zeolites to potassium feldspar due to diagenesis in a moderately to highly saline environment, and cite experimental work indicating that the formation of zeolites and potassium feldspar, rather than clay minerals, is favored by relatively high alkali-ion to hydrogen-ion ratios.

The characteristic alteration mineral assemblages of dacitic-rhyolitic lavas of the Zebulon Formation, discussed in an earlier section, are potassium feldspar + quartz + hematite. Well-preserved textures are indicative of partly glassy flows that recrystallized to this assemblage at a later date. Based on similarities with Cenozoic lavas altered by interaction with saline fluids, it is suggested that rocks of the Zebulon Formation were similarly altered. Interbedded basalt and andesite flows have primary holocrystalline textures, which may explain why they were much less affected by this alteration.

Alteration by saline fluids is highly likely for two reasons: 1) the conformably overlying Conjuror Bay Formation is interpreted as marginal marine; and 2) lavas of the Zebulon Formation were erupted shortly prior to, or during, regional extension and subsidence, resulting in the formation of a hydrographic basin. Chapin and Glazner (1983) have pointed out that many areas of potassium metasomatism in the southwestern United States are areas of regional extension.

Bloom Basalt and Fishtrap Lake Gabbro are the least altered rocks in the Bell Island Bay Group: Fe_2O_3/FeO ratios average 0.20% and CO_2 contents are low (0.00-0.60%). High and variable H_2O contents (1.70-3.80%) may either indicate a high primary water content, or be attributable to the presence of hydrated phases such as uralitic amphibole or a combination of both.

Results

Rocks of the Zebulon Formation form a continuous compositional series from basalt to rhyolite (Fig. 45). On an AFM diagram (Fig. 47), samples with relatively unaltered alkalies plot entirely within the calc-alkaline field and exhibit no iron enrichment. For the basalt-andesite range, TiO_2 values (0.56-1.9%) are low and K_2O values (0.91-4.27%) and average Al_2O_3 contents (16.9%) are high. REE analyses are only available for La and Yb; La/Yb ratios (9-17) are high, suggesting that the Zebulon Formation is LREE-enriched. Trace elements display several trends: 1) Rb, Ba, Zr, Y, Nb and Yb all correlate positively with SiO_2 content, albeit Yb very weakly; 2) Zn, Sr, Co and V display a negative correlation with SiO_2; 3) Cr, Ni and Cu have higher values in basalts, but decrease rapidly to a constant value for the andesite-rhyolite range; and 4) La is fairly constant, but more variable with increasing SiO_2 content. The basalts are LIL-element (Sr, K, Ba, Rb) enriched and are depleted in high field strength elements (elements having small ionic radii and low radius/charge ratios, Nb, P, Zr, Ti, Y, Yb) relative to N-MORB. This enrichment in LIL elements may be primary, a result of secondary alteration (Philpotts et al., 1969; Cann, 1970; Hart et al., 1974) or a combination of both.

Bloom Basalt and Fishtrap Lake Gabbro are chemically indistinguishable from major and trace element analyses (Appendices E & F). Using the classification scheme of Irvine and Baragar (1971), they range from olivine to quartz normative and no alkaline rocks are present. On an AFM diagram (Fig. 47), Bloom Basalt and Fishtrap Lake Gabbro plot in the tholeiitic field. They do not exhibit a pronounced tholeiitic differentiation trend because there is little compositional variation between samples. Ratios of Y/Nb are greater than 3, also indicating a tholeiitic character (Pearce and Cann, 1973). SiO_2 contents of the tholeiites range from 48.08-51.97%. In general, they are slightly evolved, with total iron contents between 9.1-14.8%.

Discussion

Lavas of the Zebulon Formation have chemical compositions that closely resemble those characteristic of arcs built upon continental crust. For example: 1) continental arc rocks

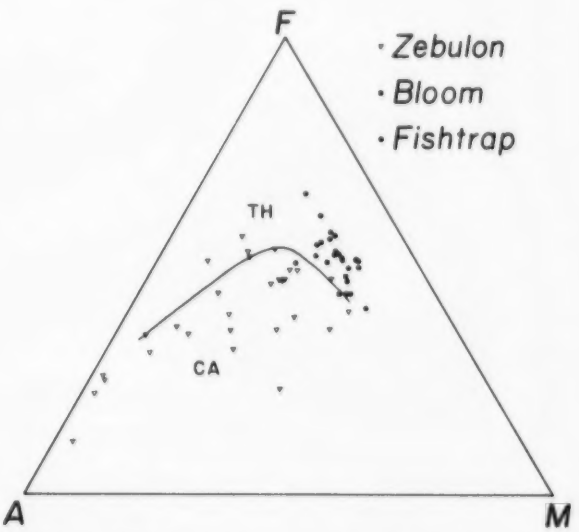

Figure 47. AFM diagram for least altered rocks from the Bell Island Bay Group. Dividing line between tholeiitic (TH) and calc-alkaline (A) fields from Irvine and Baragar (1971). Zebulon lavas plot almost entirely within the calc-alkaline field; Bloom Basalt and Fishtrap Lake Gabbro plot in the tholeiitic field. Ten of the Fishtrap Lake Gabbro analyses are from Wilson (1979).

comprise a basalt-andesite-dacite-rhyolite suite, are calc-alkaline and tend to have high Al_2O_3 and low TiO_2 (Miyashiro, 1974; Ewart, 1979, 1982; Ewart and LeMaitre, 1980); 2) erupted magmas from the continental arc suites are, for compositions greater than 51% SiO_2, consistently enriched in K_2O, by comparison with the island arc suites (Ewart, 1982); 3) calc-alkaline orogenic lavas show strong relative enrichment in the REEs and have high (ca. 10) La/Yb ratios (Ringwood, 1977; Baker, 1982); and 4) calc-alkaline basalts from active continental arcs are enriched in LIL elements and contain low abundances of the high field strength elements relative to N-MORB (Ewart, 1982; Pearce, 1983; Atherton et al., 1985).

TiO_2 contents (0.81-1.56%) of Bloom Basalt and Fishtrap Lake Gabbro are intermediate between averages for island arc tholeiites and MORBs (Jakes and Gill, 1970; Kay et al., 1970; Basaltic Volcanism Study Project, 1981) and overlap with TiO_2 values for marginal basin basalts (Hawkins, 1977). Ni (57-160 ppm) and Cr (32-280 ppm) levels are relatively low and Rb (2-41 ppm), Ba (80-320 ppm) and K_2O (0.29-1.31%) contents are moderately high relative to N-type MORB (Sun et al., 1979; Tarney et al., 1981). Overall, they are LIL-element enriched relative to MORB, with values similar to island arc tholeiites (Pearce et al., 1981) and marginal basin basalts (Saunders and Tarney, 1984). However, it cannot be ruled out that some of the high and variable K, Ba and Rb values are due to secondary alteration, because basalts typically gain these elements during seafloor diagenesis (e.g. Philpotts et al., 1969; Hart et al., 1974). Water content, which may be primary, is higher than that of normal MORB but similar to that of marginal basin basalt glasses (Tarney et al., 1981).

Ti, Y, Zr, Nb, Cr, V and REE are typically immobile during low temperature alteration and metamorphism (e.g. Philpotts et al., 1969; Cann, 1970; Bloxam and Lewis, 1972). Average Zr/Y ratios (3.4) overlap with those of ocean-floor basalts and island arc tholeiites, but are lower than ratios for continental basalts which are generally about 7.5 (Pearce and Cann, 1973; Floyd et al., 1976). The tholeiites have Ti-Y-Zr abundances similar to modern oceanic tholeiites (Sun and Nesbitt, 1977) and plot on a Ti-Y-Zr diagram (Fig. 48) in the ocean-floor basalt field. La/Yb ratios (5.2-9.8) imply slight LREE enrichment, in contrast to the generally flat, or LREE depleted patterns of MORB (Kay et al., 1970). In terms of Ti and V, the tholeiites have overlapping to higher Ti/V ratios (20-50) than typical island arc tholeiites (less than 20), but Ti/V ratios similar to MORB and continental flood basalts, although they have lower absolute abundances than the latter. The tholeiites therefore fall in the same field on a Ti/V discrimination diagram (Fig. 49) as marginal basin basalts,

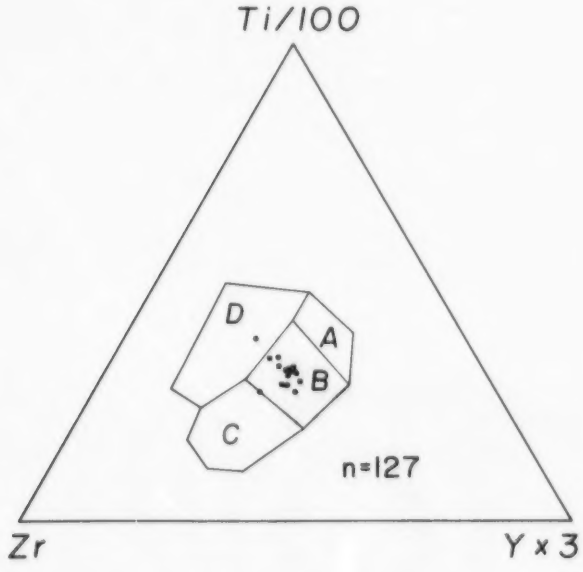

Figure 48. Ti-Y-Zr discrimination diagram (Pearce and Cann, 1973) for rocks of Bloom Basalt (squares), Fishtrap Lake Gabbro (circles) and Akaitcho Group (stippled area, N=127; after Easton, 1982). Ti-Y-Zr abundances are similar to modern oceanic tholeiites and plot in the ocean-floor basalt field. Within-plate basalts i.e. ocean island or continental basalts plot in field D, ocean-floor basalts plot in field B, low-potassium tholeiites plot in fields A and B and calc-alkaline basalts plot in fields C and B.

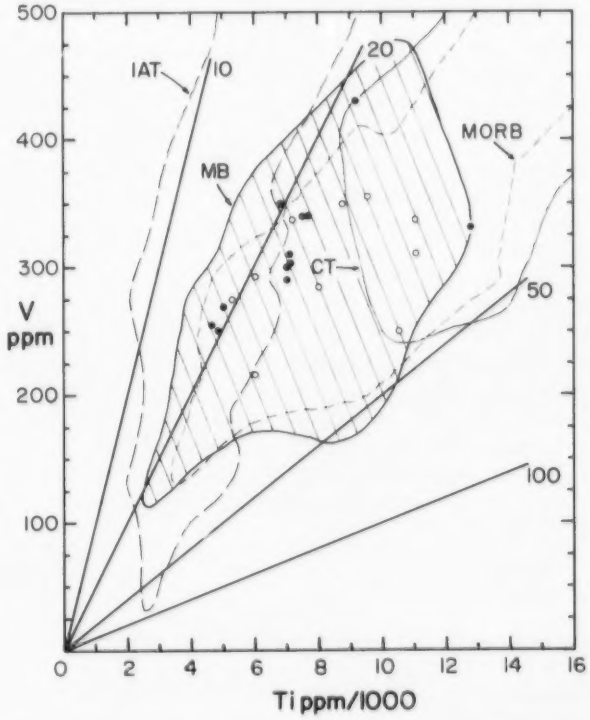

Figure 49. Ti/V discrimination diagram (Shervais, 1982) for rocks of Bloom Basalt and Fishtrap Lake Gabbro (both closed circles). Ti/V ratios are transitional between island arc tholeiites (IAT) and MORB and plot in the marginal basin basalt field (MB). Ti/V ratios from rocks of the Akaitcho Group (open circles) overlap with those from Bloom Basalt and Fishtrap Lake Gabbro (closed circles). (CT: continental tholeiite field).

which overlap both island arc tholeiite and MORB ratios, with MORB-like abundances most common (Shervais, 1982).

Overall, Bloom Basalt and Fishtrap Lake Gabbro have Ti-Y-Zr abundances similar to MORB, but have LIL-element values and La/Yb ratios similar to island arc tholeiites (IAT). Their tholeiitic chemistry, TiO_2 values and Ti/V and Zr/Y ratios are similar to both MORB and IAT. This "transitional" chemistry is typical of some marginal basin basalts, although such basalts can be extremely chemically varied, even within the same basin (Stern, 1979; Saunders et al., 1979, 1982; Tarney et al., 1981; Saunders and Tarney, 1984).

Petrogenesis

Although varying degrees of alteration rule out any detailed discussion of the petrogenesis of volcanic rocks in the Bell Island Bay Group, a fundamental chemical difference between the Zebulon Formation and Bloom Basalt/Fishtrap Lake Gabbro is manifested by a calc-alkaline versus tholeiitic character. The differences between the calc-alkaline and tholeiitic series cannot be explained by fractionation, but are more likely due to varying degrees of partial melting and depth of melting (e.g. Mysen, 1978, 1982; Masuda and Aoki, 1979; Hart and Allegre, 1980; Hutchison, 1982; Onuma et al., 1983). In conclusion, the calc-alkaline and tholeiitic basalts of the Bell Island Bay Group represent different parental melts which reflect a change in tectonic setting.

SYNTHESIS

Volcanic evolution

The Bell Island Bay Group is an assemblage of volcanic and sedimentary rocks with complex interfingering relationships typical of most continental volcanic fields. Beaverlodge Lake Sandstone, the oldest formation of the group, unconformably overlies a previously deformed and metamorphosed sialic basement complex. The formation is a fining-upward sequence of conglomerate and arkosic and lithic sandstone; undeformed volcanic clasts predominate. The formation is interpreted to represent a synvolcanic subaerially deposited alluvial fan complex. An assemblage of calc-alkaline volcanic rocks, named the Zebulon Formation, overlies and interfingers with the sandstone. The formation comprises, in ascending order, mafic to intermediate aphyric lavas intercalated with minor rhyolite block-and-ash flows and bedded tuff, a thick (350 m) rhyolite ash-flow tuff and several distinct rhyolite flow-domes intercalated with minor mafic to intermediate flows. The dominantly aphyric nature of most flows suggests high temperatures of extrusion. Overall, the volcanic rocks form a basalt-andesite-dacite-rhyolite suite. However, exact petrogenetic relationships among units are unclear due to alteration and insufficient geochronological constraints. Except for small hypabyssal intrusions, no plutonism directly related to this phase of magmatism is recognized.

Subsequent magmatism and sedimentation record a transition from a subaerial to a subaqueous depositional environment. The Conjuror Bay Formation, which conformably overlies the Zebulon Formation, contains rippled and cross-bedded mature quartzarenite and planar bedded siltstone and mudstone deposited in a marginal marine setting. Tholeiitic pillowed flows of Bloom Basalt overlie the sedimentary rocks and are intercalated with oolitic and stromatolitic patch reefs. Textures of the basalt range from aphyric to plagioclase megacrystic and glomerocrystic. Eruption in shallow water is suggested by the intercalated patch reefs and highly vesicular nature of the basalts. Gabbro sills intrusive into the pillowed flows are interpreted as comagmatic, based on similar distinctive textures and chemistry. Feeders to the flows and sills occur as north-trending gabbroic dykes that cut the sialic basement complex.

In conclusion, the Bell Island Bay Group records a transition from: 1) subaerial to subaqueous deposition; 2) a continental to a marginal marine environment; 3) calc-alkaline to tholeiitic magmatism; and 4) a basalt-andesite-dacite-rhyolite suite to a fundamentally basaltic suite.

Tectonic setting

Any tectonic interpretation for the Bell Island Bay Group must integrate the stratigraphy, chemistry, structure and overall volcanic evolution of the group, in addition to its regional geological setting. Some important points to consider for interpretion of the tectonic setting of the group are: 1) volcanic rocks of the Bell Island Bay Group were erupted through and onto sialic crust (Hottah Terrane); 2) magmatic evolution of the group is from a heterogeneous calc-alkaline series (Zebulon Formation) to a homogeneous tholeiitic basalt suite (Bloom Basalt and Fishtrap Lake Gabbro); 3) the depositional environment was subaerial during calc-alkaline magmatism and subaqueous during tholeiitic magmatism; and 4) the subaqueous environment is interpreted as shallow marine.

Volcanic rocks of the Zebulon Formation form a calc-alkaline basalt-andesite-dacite-rhyolite suite, with rocks of intermediate composition most abundant. Calc-alkaline series rocks occur mainly in island and continental margin arcs, although they do occur infrequently in other environments such as continental and oceanic rifts, ocean islands and tholeiitic basalt provinces (Miyashiro, 1975; Gill, 1981). However, basalts usually predominate in the latter settings, and associated intermediate rocks generally differ from arc volcanic rocks in TiO_2 contents and other respects (Gill, 1981). The Zebulon Formation is closely comparable in both chemical composition and styles of volcanism to Cenozoic continental arcs. The formation is a high-potassium calc-alkaline suite with low TiO_2 content and high La/Yb, Al_2O_3 and K_2O values similar to continental arcs related to subduction such as the Andes (Thorpe and Francis, 1979), the Cascades (McBirney, 1978; McBirney and White, 1982), Japan (Kuno, 1959; Miyashiro, 1974; Aramaki and Ui, 1982) and the Alaskan Peninsula (Burk, 1965; Marsh, 1982).

On a regional scale, the Zebulon Formation both overlies and is overlain by volcanic-plutonic suites best interpreted as continental arcs. They are respectively, Hottah Terrane (Hildebrand and Roots, 1985) and the Great Bear Magmatic Zone (Hildebrand, 1982; Hildebrand et al., 1987b). Spatially and temporally, the regional tectonic setting of the Zebulon Formation therefore is compatible with a continental magmatic arc.

In contrast to rocks of the calc-alkaline series, tholeiitic basalts occur in almost all tectonomagmatic settings, and as a result numerous geochemical discriminant diagrams have been developed to determine the tectonic setting of basic volcanic rocks, where this cannot be ascertained from the geology. In the case of Bloom Basalt and Fishtrap Lake Gabbro, the benefit of both detailed mapping within a regional context coupled with geochemistry allows the elimination of several possible tectonic settings. For instance, oceanic intraplate volcanism (e.g. Hawaii), though tholeiitic in character, has neither major or minor element chemistry nor geological setting in common with Bloom Basalt and Fishtrap Lake Gabbro (Basaltic Volcanism Study Project, 1981). It is not unusual for island arcs to have both calc-alkaline and tholeiitic suites; however, the tholeiitic suite is older than the calc-alkaline suite as a rule (Jakes and White, 1972; Gill, 1981), the reverse of the Bell Island Bay Group. In island arcs that do have tholeiitic basalts, such as Japan (Kuno, 1959), the basalts do not occur in successions several kilometres thick, as does Bloom Basalt. In addition, typical island arcs are not built upon sialic crust (Miyashiro, 1974; Baker, 1982).

Predominantly basaltic magmatism, or the bimodal rhyolite-basalt suite, occurs in Cenozoic volcanic fields characterized by extension. In the Great Basin of the western United States, the transition from predominantly calc-alkaline intermediate rocks to fundamentally basaltic volcanism is considered to be an effect of regional extension indicated by Basin and Range normal faulting and the intrusion of numerous dykes (Scholtz et al., 1971; Christiansen and Lipman, 1972; Christiansen and McKee, 1978). Mid-ocean ridges, extensional features related to seafloor spreading, and marginal basins, related to extension within a magmatic arc, are both characterized by basaltic volcanism (Kay et al., 1970; Hawkins, 1977; Saunders and Tarney, 1984). The subaerial to subaqueous transition evident in rocks of the Bell Island Bay Group, coupled with a sharp change in chemical composition to predominantly basaltic magmatism, and the consistent northerly trend of feeder dykes in the basement, when taken together, clearly indicate an extensional stress regime during at least the tholeiitic phase of magmatism. The prevailing stress regime during the early subaerial eruptions is uncertain.

Marginal basin rocks are the one volcanic group that share all the salient features with Bloom Basalt and Fishtrap Lake Gabbro, such as: association with a change from calc-alkaline to tholeiitic magmatism (Tarney et al., 1981); predominance of basaltic magmatism with chemistry transitional between mid- ocean ridge basalts and arc tholeiites (Hawkins, 1977; Tarney et al., 1981; Saunders and Tarney, 1984); and eruption during extension, subsidence and marine innundation (Karig, 1971a,b).

In conclusion, the Bell Island Bay Group can easily and logically be interpreted to represent volcanism within an extending and subsiding continental arc (Reichenbach, 1985b, 1986a,b). Karig (1971a,b) referred to extensional basins lying behind island arcs and floored by oceanic crust as marginal basins. However, there is no evidence that extensional processes associated with the eruption of Bloom Basalt led to the generation of oceanic crust. In addition, the basin formed in an arc that developed on continental, rather than oceanic crust. The term ensialic marginal basin is therefore appropriate. Marginal basins in intra-oceanic settings are indeed more common than at continental margins, possibly due to the thickness, strength and rigidity of continental, as opposed to oceanic lithosphere (Toksoz and Bird, 1977). Nonetheless, several well-documented examples of marginal basins formed at continental margins exist: the Mesozoic marginal basins of southern Chile (Dalziel et al., 1974; Saunders et al., 1979; Bartholomew and Tarney, 1984), central Chile (Aberg et al., 1984) and central Peru (Atherton et al., 1983, 1985); and Cenozoic marginal basins such as the proto-Gulf of California (Karig and Jensky, 1972; Saunders et al., 1982), Okinawa Trough (Letouzey and Kimura, 1985), Japan Sea (Uyeda and Miyashiro, 1974) and Bransfield Strait (Weaver et al., 1979). These basins may be floored by either attenuated continental crust (e.g. central Chile), or by oceanic crust (e.g. southern Chile). Thus, the tectonic setting of the Bell Island Bay Group is considered analogous to these Mesozoic to Recent examples of continental arc-ensialic marginal basin pairs.

Regional correlations

About 120 km east of the Bell Island Bay Group, in the internal zone of Wopmay Orogen, metavolcanic and metasedimentary rocks of the Akaitcho Group occur at the base of the Coronation Supergroup (Hoffman et al., 1978; Easton, 1982; Hoffman, 1984b). Regional metamorphic grade ranges from greenschist to granulite grade (Easton, 1982) and, to an extent, metamorphism is spatially related to the Hepburn Batholith (St-Onge, 1981). The group is structurally complex, which hinders accurate thickness estimates and correlations along strike (St-Onge et al., 1982; King, 1985). However, Easton (1980, 1982) defined a very generalized stratigraphy, in ascending order: pillowed and massive basalt flows and sills, arkosic turbidites, bimodal submarine volcanic complexes and both pelitic and carbonate sedimentary rocks. U-Pb (zircon) ages for rhyolites in the upper Akaitcho Group, and the correlative Grant Group, range from 1895-1902 Ma (Bowring, 1984, 1985).

The overall eruptive sequence of the Akaitcho basalts (see Easton, 1982) proceeded from evolved continental tholeiites, through continental tholeiites, to oceanic tholeiites. Respective REE patterns vary from LREE enriched to flat. La/Yb ratios range from 1.2-9.2. The basalts have Ti-Y-Zr abundances similar to oceanic tholeiites, and on a Ti-Y-Zr diagram plot in the ocean-floor basalt field. Based on stratigraphy and

chemistry, rocks of the Akaitcho Group are interpreted to be continental rift deposits (Hoffman et al., 1978; Easton, 1980, 1981, 1982).

An understanding of the relationship between the Akaitcho Group and the Slave Craton is somewhat unclear due to structural complexity, lateral facies changes and key units yet to be dated in ongoing geochronological studies. However, observations to date include: 1) in the Kapvik Lake area, exposed basement that lies unconformably beneath the Akaitcho Group (Easton, 1982; Hoffman, 1984b) has a U-Pb (zircon) age of 2569 ± 10 Ma (Bowring, 1985); 2) the necessity of a continental source terrane for the voluminous arkoses and granite cobble-bearing conglomerates of the Akaitcho Group (Easton, 1980, 1982) that have both Archean (2700 Ma) and early Proterozoic (2035 Ma) detrital zircon ages (Bowring, 1985); 3) rhyolites within the group are considered volumetrically too large to have been fractionated from basaltic magma and are interpreted as crustal melts (Easton, 1982); and 4) consistent association of Akaitcho units with thrusted Archean continental crust fragments (King, 1986). Thus, the data strongly suggest that the Akaitcho Group was deposited close to, or directly onto, either Archean (Slave Craton?) and/or early Proterozoic (Hottah Terrane?) continental crust.

Relationships between rift deposits of the Akaitcho Group and overlying passive-margin siliciclastics of the Odjick Formation (Hoffman, 1972, 1973) are no less complex. Easton (1980, 1982) interpreted pelites of the Odjick Formation to conformably overlie Akaitcho Group rocks east of the Hepburn Batholith. In addition, King (1986) discussed a possible lateral transition between rift facies of the Akaitcho Group and passive margin facies of the Odjick Formation in the south-central part of the internal zone. Because rocks of the Odjick Formation undisputedly onlap Archean crust of the Slave Province (Hoffman, 1972, 1973), the interpretation of a conformable and/or transitional relationship between the Odjick Formation and Akaitcho Group is critical, because if correct, it indicates that at least part of the Akaitcho Group was deposited directly onto Archean rocks of the Slave Province and not exotic Archean crust.

Bloom Basalt and Fishtrap Lake Gabbro of the Bell Island Bay Group are similar to rocks of the Akaitcho and Grant groups in the following ways.

1. Lithology: the predominance of basaltic rocks and lack of intermediate compositions, similar plagioclase glomeroporphyritic gabbro sills, the presence of intercalated sedimentary rocks and eruption in a marine environment.

2. Geochemistry: tholeiitic character, La/Yb ratios, Ti/V ratios (Fig. 49) and Ti-Y-Zr abundances.

3. Age (?): although neither Bloom Basalt nor Fishtrap Lake Gabbro has been dated, a rhyolite flow at the top of the underlying Zebulon Formation is 1898 ± 7 Ma, which overlaps with ages clustering around 1900 Ma from the Akaitcho Group; because the Bell Island Bay Group is a conformable sequence, there is no reason to suspect that rocks of Bloom Basalt or Fishtrap Lake Gabbro are significantly younger than 1898 Ma.

In summary, based on lithology, geochemistry and age, Bloom Basalt and Fishtrap Lake Gabbro are correlated with rocks of the Akaitcho and Grant groups. If this conclusion is correct, then rocks of these formations and groups were erupted and emplaced within the same basin. This basin is here termed the Akaitcho Seaway.

Plate tectonic model

Previous interpretations for the tectonic evolution of Wopmay Orogen have proposed a Wilson Cycle model (Hoffman, 1980a) involving crustal stretching, with the deposition of rift facies rocks (Akaitcho Group) and the development of a passive margin (Odjick and Rocknest formations). This was followed by margin collapse into a foredeep concurrent with collision of an exotic terrane (Hottah Terrane, Hildebrand, 1981) with Slave Craton above a west-dipping subduction zone (Hoffman, 1980a). This collision (Calderian Orogeny) produced a metamorphic-plutonic internal zone (St-Onge et al., 1982, 1983, 1984) and a thin-skinned thrust-fold belt (Tirrul, 1982, 1983). Following collision, an east-dipping subduction zone led to the formation of a calc-alkaline continental arc, the Great Bear Magmatic Zone (Hildebrand, 1981; Hildebrand and Bowring, 1984). However, the geology, geochemistry and geochronology of the Bell Island Bay Group suggests that the orogen better represents evolving tectonism and magmatism in a continental arc–back-arc complex (Fig. 50). Thus, modifications to the tectonic model for Wopmay Orogen resulting from research on the Bell Island Bay Group agree in essence with preliminary models recently proposed by Hildebrand and Roots (1985) and Hildebrand et al. (1987b), but for some alternative reasons.

In the model presented here, the lower calc-alkaline suite (Zebulon Formation) of the Bell Island Bay Group is interpreted to represent a continental arc formed above an east-dipping subduction zone. Extension within the arc led to subsidence, marine innundation, eruption of tholeiitic basalts (Bloom Basalt) and emplacement of hypabyssal sills (Fishtrap Lake Gabbro). Tholeiitic volcanic rocks and sills of the Akaitcho and Grant groups, in the internal zone to the east, are correlated with Bloom Basalt and Fishtrap Lake Gabbro of the Bell Island Bay Group. Tholeiitic rocks of all three groups are therefore considered to have formed within the same marginal basin.

Rocks deposited on the western side of the Akaitcho Seaway (Bloom Basalt) are pinned to Hottah Terrane by feeder dykes (Fishtrap Lake Gabbro) that can be traced from basement rocks into the overlying pillow basalts; rocks deposited on the extreme eastern side (Akaitcho Group) unconformably overlie Archean basement. If it is assumed that the Archean basement is not exotic with respect to Slave Craton, then the model presented here requires Hottah Terrane to have been part of Slave Craton during the deposition of Beaverlodge Lake Sandstone and that volcanic rocks of the Zebulon Formation resulted from easterly-directed subduction. Hildebrand and Roots (1985) hypothesized that a Hottah arc was contiguous to Slave Craton prior to a 1900 Ma rifting event, and that deformation of Hottah Terrane was caused by basin closure (Calderian Orogeny). However,

because nonpenetratively strained rocks of the Bell Island Bay Group unconformably overlie penetratively strained rocks of Hottah Terrane, and the Bell Island Bay Group predates the Calderian Orogeny, the penetrative deformation of Hottah Terrane cannot have been caused by the Calderian Orogeny. The origin of the deformation in rocks of Hottah Terrane remains problematic.

Details on the original size of the basin are complicated by deformation during basin closure and cover by younger rocks of the Great Bear zone. Assuming a simplistic model of one continuous basin, an estimate for its width is 150 km, obtained by measuring the greatest distance between correlative units perpendicular (east-west) to the ancient continental margin. This is necessarily a minimum width, because deformation during the Calderian Orogeny resulted in tectonic shortening, and may have involved subduction or underthrusting of part of the basin floor. The only quantitative estimates of shortening are from work in the foreland thrust-fold belt using down-plunge projections (Tirrul, 1982, 1983). Tirrul's (1982, 1983) minimum estimate of shortening (east-west) was 40 percent. Thus, as an absolute minimum estimate, the width of the basin was 216 km.

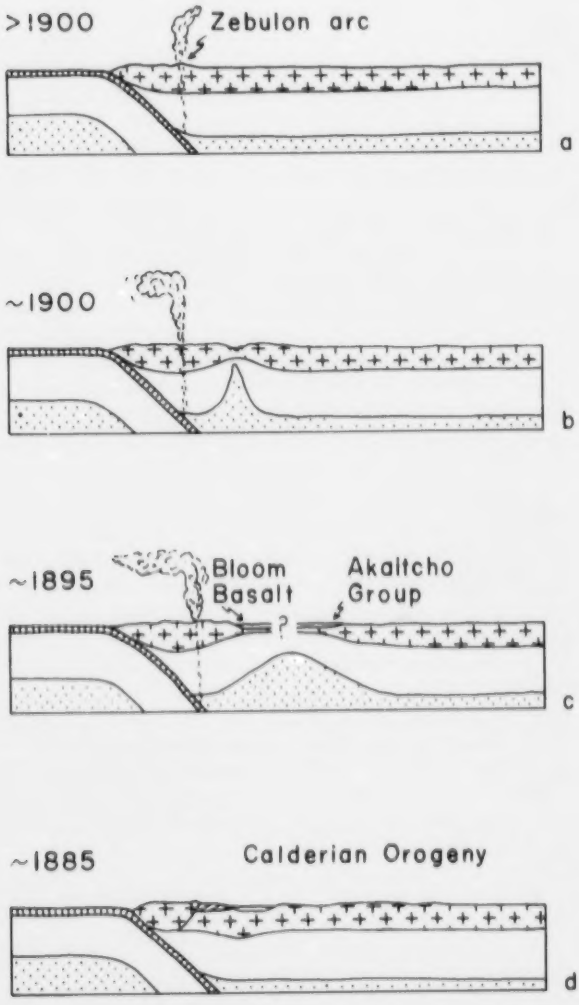

Figure 50. Tectonic model for the Bell Island Bay Group: a) eastward subduction beneath Hottah Terrane, interpreted to be contiguous to the Slave Craton at this time, results in the initiation of the "Zebulon arc" with eruption of lavas of the Zebulon Formation; b) extension within the arc leads to subsidence, marine inundation and formation of an ensialic marginal basin; c) tholeiitic pillow basalt of Bloom Basalt and the Akaitcho Group, and associated gabbro sills, are erupted and emplaced within a marginal basin setting; and d) basin closure results in the Calderian Orogeny.

Uncertainties surround the nature of the floor of the basin. Along the western margin, Bloom Basalt was erupted through sialic crust. At this locale, the marginal basin deposits directly overlie the Zebulon Formation. Thus, present exposures of the Bell Island Bay Group are proximal to the arc, and only tholeiites that erupted during the early stages of extension are exposed. To the east, all exposures of the Akaitcho and Grant groups are consistently associated with fragments of Archean basement. In addition, voluminous rhyolites of the Akaitcho Group are interpreted as crustal melts (Easton, 1982). Based on observations to date, it is unlikely that new oceanic crust was ever generated within the marginal basin. However, future mapping in Wopmay Orogen may reveal outliers of marginal basin rocks that could resolve this question.

CONCLUSIONS

1. The 4.5 km thick Bell Island Bay Group sits unconformably upon an older sialic basement complex (Hottah Terrane). It contains five formations, from oldest to youngest: 1) subaerially deposited conglomerate and sandstone (Beaverlodge Lake Sandstone); 2) subaerially erupted calc-alkaline volcanic rocks ranging in composition from basalt to rhyolite (Zebulon Formation); 3) shallow marine siliciclastics (Conjuror Bay Formation); 4) tholeiitic pillow basalts (Bloom Basalt); and 5) tholeiitic gabbro sills and dykes (Fishtrap Lake Gabbro) interpreted to be comagmatic with the basalts.

2. The subaerial calc-alkaline basalt-andesite-dacite-rhyolite suite (Zebulon Formation) is interpreted to represent volcanism of a continental arc.

3. The tholeiitic pillow basalts (Bloom Basalt) and comagmatic gabbroic intrusions (Fishtrap Lake Gabbro) have chemical characteristics transitional between MORBs and arc tholeiites. This, coupled with east-west extension during tholeiitic magmatism as documented by the north trend of coeval gabbroic dykes, suggests that the upper subaqueous formations of the Bell Island Bay Group were deposited within a north-trending marginal basin.

4. A U-Pb (zircon) age of 1898 Ma, obtained from a rhyolite flow in the Zebulon Formation, implies that: 1) the penetrative deformation of Hottah Terrane occurred prior to the Calderian Orogeny; and 2) rocks of the Bell

Island Bay Group are coeval with rocks of the Akaitcho and Grant groups and should not be included within the Great Bear Magmatic Zone.

5. Based on similarities in lithology, chemistry and age, tholeiitic rocks of the Bell Island Bay Group (Bloom Basalt, Fishtrap Lake Gabbro) are correlated with rocks of the Akaitcho and Grant groups. This implies that rocks of all three groups were deposited in the same marginal basin and supports a back-arc setting for the Coronation Supergroup.

6. If the Akaitcho, Grant and Bell Island Bay groups were all deposited within the same marginal basin, and are not exotic with respect to the Slave Craton and the rest of the Coronation Supergroup, then the arc-like volcanic rocks of the Zebulon Formation resulted from easterly-directed subduction, as there was no ocean to the east. Extension within the arc led to the formation of an ensialic marginal basin between Hottah Terrane and Slave Craton. Implications of this model are: 1) the Calderian Orogeny is the result of closure of the marginal basin rather than a deformational event caused by collision between Slave Craton and an exotic microcontinent; and 2) Wopmay Orogen may represent tectonism and magmatism in an evolving Andean-type plate margin, rather than a Wilson Cycle.

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APPENDIX A

Chemical analyses of basalts of the Zebulon Formation. Major elements in weight % and trace elements in ppm. l, lower member; u, upper member.

	R84-104$_l$	R84-46$_l$	R84-186$_l$	R84-102$_l$	R84-227$_u$	R84-172$_l$	R84-120B$_l$
SiO_2	46.60	48.80	48.40	49.00	48.30	49.90	49.50
TiO_2	1.29	1.86	0.81	0.85	0.74	0.91	1.30
Al_2O_3	16.00	16.50	16.10	16.80	13.80	16.80	16.70
Fe_2O_3	5.20	6.60	6.20	5.20	3.90	4.50	7.20
FeO	5.90	4.90	5.00	5.60	6.00	5.50	2.60
MgO	5.93	5.88	5.66	7.59	9.90	5.34	1.25
MnO	0.39	0.35	0.45	0.29	0.26	0.31	0.56
CaO	6.39	6.00	7.61	6.32	6.73	6.02	6.82
Na_2O	3.60	4.16	3.80	2.84	2.90	5.19	3.81
K_2O	1.56	2.07	1.83	1.42	1.44	0.87	4.02
P_2O_5	0.36	0.36	0.17	0.17	0.16	0.20	0.32
H_2O	3.60	2.90	2.30	3.30	3.30	2.40	1.70
CO_2	3.40	1.10	2.10	1.70	1.90	1.40	5.50
total	100.22	101.48	100.43	101.08	99.33	99.34	101.28
V	190	290	180	210	220	190	260
Cr	310	110	440	310	840	32	69
Co	74	51	49	49	54	43	29
Ni	220	110	190	190	280	77	76
Cu	68	23	17	16	11	16	22
Zn	310	390	160	200	180	270	42
Rb	64	70	93	55	62	29	220
Sr	210	260	200	250	320	430	70
Y	24	37	21	16	19	22	28
Zr	140	200	88	78	76	100	160
Nb	9	7	6	5	8	5	10
Ba	240	590	330	190	370	160	140
La	30	39	27	30	19	26	35
Yb	2.6	3.4	2.4	1.7	1.9	2.5	2.7

APPENDIX B

Chemical analyses of intermediate flows of the Zebulon Formation. Major elements in weight % and trace elements in ppm. l, lower member; u, upper member.

	R84-202$_u$	R84-155$_l$	R84-121$_l$	R84-23$_l$	R84-66$_l$	R84-344$_u$	83R-80$_l$	R84-233$_l$	R84-157$_l$	R84-32$_l$	R84-105$_l$	R84-200$_l$	R84-73A$_l$
SiO_2	51.60	51.00	51.00	52.40	52.60	52.40	55.30	54.60	53.30	56.50	57.10	58.80	58.00
TiO_2	0.90	0.81	1.47	0.82	1.36	1.87	1.25	1.31	1.44	1.28	0.79	1.06	0.68
Al_2O_3	16.90	17.00	16.30	17.10	15.90	14.50	16.60	15.40	16.80	17.70	15.90	16.80	15.60
Fe_2O_3	8.00	8.10	4.40	2.00	3.90	7.90	4.70	4.10	3.60	4.30	3.00	3.10	2.60
FeO	4.50	4.10	3.00	6.00	5.70	5.40	3.40	5.50	3.30	2.70	3.30	4.50	3.80
MgO	5.03	4.55	1.37	6.43	2.88	4.70	0.92	2.13	4.03	1.91	2.94	2.43	5.02
MnO	0.28	0.19	0.69	0.36	0.44	0.34	0.35	0.34	0.27	0.11	0.17	0.21	0.18
CaO	4.86	6.59	7.24	6.79	6.77	3.08	5.53	6.58	5.63	2.28	5.81	3.91	4.95
Na_2O	3.92	3.40	4.40	3.97	3.44	4.42	7.25	3.18	5.16	5.34	3.11	4.97	3.50
K_2O	3.00	2.40	3.75	1.91	2.69	1.42	1.00	1.76	1.72	4.00	3.81	2.13	2.44
P_2O_5	0.19	0.21	0.48	0.19	0.48	0.33	0.42	0.45	0.51	0.42	0.23	0.49	0.17
H_2O	2.30	2.60	1.70	2.60	1.30	2.70	1.10	1.90	2.00	1.70	2.00	1.30	2.30
CO_2	0.60	2.90	5.4	0.20	2.80	0.30	3.00	2.50	2.70	2.50	3.10	0.30	1.70
total	100.08	100.85	101.20	100.77	100.26	99.16	100.82	99.65	100.48	100.74	101.06	100.05	100.92
V	190	180	180	210	140	420	110	180	150	110	130	46	130
Cr	27	37	21	130	5	36	1	23	7	14	76	0	84
Co	38	38	21	31	30	48	11	31	35	15	30	13	30
Ni	87	100	21	71	45	39	31	26	36	18	100	40	100
Cu	17	12	34	18	14	2	11	12	3	3	24	9	67
Zn	120	140	69	300	120	490	91	180	250	47	150	150	180
Rb	120	85	210	54	130	48	33	67	59	190	99	45	72
Sr	290	290	89	550	300	78	120	370	200	48	300	480	260
Y	22	20	41	18	36	34	47	34	41	42	21	48	19
Zr	100	95	210	110	190	150	210	190	220	220	150	480	130
Nb	7	5	7	8	11	12	11	8	10	11	10	14	8
Ba	620	280	190	640	290	280	210	340	240	270	590	530	530
La	25	24	42	22	40	34	41	41	40	34	37	48	32
Yb	2.5	1.8	3.8	1.3	3.7	3.6	4.5	3.5	3.6	4.1	2.2	4.9	2.1

	R84-129$_l$	83R-1$_l$	R84-336$_l$	R84-147$_l$	R84-368$_l$	R84-170$_l$	R84-154$_l$	R84-237$_u$	R84-388$_l$	R84-178$_l$	R84-91$_l$	R84-153$_l$
SiO_2	58.90	58.00	61.30	62.20	63.20	63.10	63.60	63.90	64.60	65.20	68.70	68.90
TiO_2	1.19	0.54	0.55	0.56	1.06	0.90	0.57	0.71	0.48	0.50	0.54	0.53
Al_2O_3	16.40	15.20	14.80	15.30	14.40	17.60	15.40	16.70	15.30	15.50	14.40	14.10
Fe_2O_3	4.20	1.80	8.90	1.70	7.00	4.30	6.90	4.00	6.40	3.20	4.40	4.30
FeO	3.60	5.00	0.76	3.70	0.50	1.60	0.30	1.20	0.50	0.20	0.20	0.30
MgO	1.41	7.36	0.77	3.04	0.18	0.91	0.12	1.27	0.38	0.10	0.17	0.02
MnO	0.38	0.26	0.03	0.14	0.02	0.03	0.01	0.08	0.01	0.01	0.02	0.00
CaO	6.35	2.99	0.52	3.12	0.72	0.78	0.17	1.01	0.06	0.22	0.25	0.22
Na_2O	3.88	2.70	0.51	3.18	0.43	5.35	0.31	4.06	0.20	0.22	0.85	0.20
K_2O	1.70	1.76	10.20	4.20	10.90	3.38	11.00	5.21	10.10	12.00	9.64	10.40
P_2O_5	0.47	0.14	0.13	0.14	0.46	0.41	0.13	0.24	0.01	0.13	0.14	0.15
H_2O	0.70	3.70	0.90	1.70	0.60	1.00	0.40	1.10	1.20	0.50	0.50	0.40
CO_2	1.50	0.30	0.10	1.60	0.00	0.20	0.10	0.40	0.10	0.00	0.10	0.00
total	100.68	99.75	99.41	101.48	99.47	99.58	99.01	99.88	99.34	97.78	99.91	99.52
V	92	130	130	110	78	34	16	25	21	17	18	19
Cr	7	290	250	100	15	0	0	12	14	11	0	3
Co	19	35	7	23	6	11	4	6	3	3	6	5
Ni	39	130	72	66	45	32	31	24	29	20	39	37
Cu	11	0	0	38	2	3	1	37	0	4	6	5
Zn	150	260	32	160	17	39	33	71	26	40	26	23
Rb	64	43	290	110	380	150	300	160	330	300	290	270
Sr	330	300	40	170	46	90	10	49	13	17	25	23
Y	41	13	21	19	41	41	57	54	58	50	43	46
Zr	210	110	130	130	240	820	400	440	480	400	400	380
Nb	10	10	9	9	13	11	18	13	21	20	17	19
Ba	290	380	1600	560	1500	410	330	760	760	440	560	510
La	39	12	30	31	48	33	53	51	42	55	61	68
Yb	4.0	0.7	2.1	1.8	3.4	5.6	5.7	5.2	5.0	4.6	4.3	4.4

APPENDIX C

Chemical analyses of rhyolite ash-flow tuff of the Zebulon Formation. Major elements in weight % and trace elements in ppm.

	R84-160	R84-361	R84-3521	R84-3520
SiO_2	71.50	75.60	77.20	76.80
TiO_2	0.14	0.08	0.13	0.14
Al_2O_3	13.40	11.20	11.10	10.70
Fe_2O_3	4.60	2.00	2.20	2.30
FeO	0.00	0.20	0.60	0.40
MgO	0.05	0.06	0.29	0.23
MnO	0.00	0.01	0.01	0.01
CaO	0.04	0.07	0.07	0.07
Na_2O	0.12	0.27	0.23	0.20
K_2O	8.48	9.32	7.16	6.70
P_2O_5	0.08	0.04	0.02	0.05
H_2O	0.70	0.30	0.70	0.80
CO_2	0.10	0.00	0.00	0.10
total	99.21	99.15	99.71	98.50
V	22	11	14	12
Cr	0	10	8	8
Co	8	1	2	2
Ni	26	25	27	19
Cu	12	0	5	0
Zn	35	49	19	19
Rb	290	260	210	210
Sr	21	15	17	15
Y	77	67	32	33
Zr	340	220	350	340
Nb	25	37	17	23
Ba	210	910	950	610
La	130	32	61	83
Yb	5.4	4.9	3.0	2.5

APPENDIX D

Chemical analyses of rhyolite flows of the ZebulonFormation. Major elements in weight % and trace elements in ppm. l, lower member; u, upper member; *, hypabyssal intrusion.

	84-23$_u$	84-24$_u$	R84-262$_u$	83R-84$_u$	R84-323$_l$	84-30$_u$	R84-180$_u$
SiO_2	69.10	69.00	70.20	72.20	72.00	71.40	75.30
TiO_2	0.66	0.63	0.26	0.08	0.08	0.11	0.12
Al_2O_3	14.20	15.00	13.40	13.80	13.00	15.60	13.20
Fe_2O_3	2.00	5.10	3.30	1.60	1.50	4.40	2.60
FeO	2.80	0.70	0.40	0.20	0.20	0.30	0.00
MgO	2.72	0.88	0.14	0.27	0.09	0.48	0.24
MnO	0.04	0.01	0.01	0.02	0.01	0.01	0.01
CaO	0.33	0.19	0.09	0.12	0.08	0.05	0.04
Na_2O	1.33	0.11	0.04	1.17	0.24	0.13	0.07
K_2O	4.19	4.99	9.80	9.06	10.90	4.84	7.94
P_2O_5	0.15	0.14	0.04	0.02	0.01	0.03	0.04
H_2O	2.60	2.30	0.60	0.60	0.30	2.30	0.90
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.10
total	100.12	99.05	98.28	99.14	98.41	99.65	100.56
V	41	35	22	4	10	11	29
Cr	17	12	9	2	5	7	12
Co	8	1	2	0	3	0	8
Ni	20	12	32	11	45	5	28
Cu	0	0	6	0	0	0	18
Zn	85	63	25	23	29	20	27
Rb	160	270	280	210	270	210	240
Sr	33	3	15	18	31	4	15
Y	50	65	48	22	26	48	39
Zr	420	460	240	130	310	330	280
Nb	21	22	22	16	16	28	17
Ba	500	250	1000	400	1700	40	330
La	66	82	52	26	19	36	50
Yb	4.0	4.8	4.1	2.8	3.1	3.6	4.6

	R84-212$_u$	R84-260A$_u$	R84-79A*	R84-222$_u$	R84-359$_l$	R84-204$_u$	R84-247$_u$
SiO_2	76.40	76.10	75.80	76.00	76.50	78.60	79.60
TiO_2	0.12	0.09	0.04	0.12	0.07	0.13	0.13
Al_2O_3	13.40	12.20	12.50	10.90	11.30	11.90	11.00
Fe_2O_3	0.50	0.40	0.10	1.60	0.90	1.10	1.10
FeO	0.30	0.40	0.20	0.30	0.20	0.00	0.00
MgO	0.13	0.20	0.18	0.14	0.05	0.30	0.01
MnO	0.01	0.03	0.01	0.01	0.01	0.01	0.00
CaO	0.07	0.27	0.09	0.08	0.07	0.09	0.04
Na_2O	0.17	0.05	0.16	0.18	0.13	0.38	0.05
K_2O	9.10	8.81	8.80	8.55	9.04	7.24	8.16
P_2O_5	0.02	0.02	0.02	0.01	0.03	0.06	0.04
H_2O	0.50	0.70	0.60	0.50	0.30	0.70	0.50
CO_2	0.00	0.40	0.10	0.00	0.00	0.10	0.10
total	100.72	99.67	98.60	98.39	98.60	100.61	100.73
V	5	6	4	10	7	12	13
Cr	3	3	3	5	4	7	4
Co	3	3	2	3	1	6	4
Ni	38	37	19	21	11	29	30
Cu	10	36	36	65	0	10	15
Zn	18	76	47	18	10	14	22
Rb	240	270	180	280	230	180	240
Sr	23	29	17	12	14	18	20
Y	42	27	57	70	23	55	40
Zr	300	210	90	230	240	190	250
Nb	22	52	21	30	18	17	32
Ba	1500	1400	460	470	300	430	390
La	31	6	19	92	46	61	42
Yb	4.7	4.0	5.8	5.8	2.9	4.0	4.5

APPENDIX E

Chemical analyses of Bloom Basalt. Major elements in weight % and trace elements in ppm.

	R84-266	83R-79	83R-68	C84-152	R84-338	83R-62
SiO_2	47.60	48.60	50.00	50.70	49.30	67.10
TiO_2	0.84	1.15	1.18	1.18	1.08	0.40
Al_2O_3	17.10	15.40	14.30	14.40	13.40	16.30
Fe_2O_3	1.50	2.20	2.90	2.30	2.40	1.20
FeO	9.10	8.80	9.80	10.60	9.70	3.40
MgO	8.18	6.81	6.49	8.06	7.44	1.76
MnO	0.23	0.20	0.38	0.27	0.23	0.05
CaO	11.00	11.10	10.50	7.65	9.70	0.39
Na_2O	2.20	2.06	3.35	3.72	2.80	0.67
K_2O	1.08	0.88	0.29	0.52	0.52	5.90
P_2O_5	0.09	0.14	0.14	0.12	0.13	0.15
H_2O	2.30	3.30	2.10	1.70	3.30	2.50
CO_2	0.10	0.20	0.00	0.00	0.20	0.20
total	101.32	100.84	101.41	101.22	100.20	100.02
V	270	290	310	340	350	57
Cr	170	130	54	140	280	44
Co	59	47	47	51	52	8
Ni	150	94	70	85	78	37
Cu	73	150	130	87	120	4
Zn	120	95	110	160	140	34
Rb	28	8	2	11	9	290
Sr	180	210	110	100	150	28
Y	14	23	29	31	20	37
Zr	54	75	81	79	71	170
Nb	4	5	7	8	4	16
Ba	320	110	90	140	150	850
La	17	20	21	11	14	23
Yb	1.9	2.5	2.6	2.1	2.2	3.1

APPENDIX F

Chemical analyses of Fishtrap Lake Gabbro. Major elements in weight % and trace elements in ppm.

	R84-272	C84-151	R84-379	R84-173	R84-G5	83R-61	R84-98
SiO_2	49.90	50.30	49.50	49.50	49.50	49.60	50.70
TiO_2	1.54	1.19	0.84	1.15	0.78	1.15	2.13
Al_2O_3	13.50	14.50	16.20	14.20	15.40	13.70	13.70
Fe_2O_3	3.50	2.00	1.30	4.60	1.20	2.30	8.20
FeO	9.90	10.70	7.80	8.00	7.90	9.90	6.60
MgO	5.57	6.57	8.13	6.69	8.32	6.75	4.15
MnO	0.29	0.36	0.18	0.24	0.19	0.24	0.22
CaO	11.30	9.25	9.70	9.48	9.80	7.58	8.24
Na_2O	2.28	3.29	2.20	1.95	2.64	3.98	2.39
K_2O	0.47	0.58	1.27	1.22	0.64	0.28	0.70
P_2O_5	0.16	0.12	0.08	0.14	0.09	0.14	0.41
H_2O	2.30	2.50	3.30	2.60	3.10	3.60	2.40
CO_2	0.20	0.10	0.10	0.60	0.20	0.30	0.50
total	101.91	101.46	100.60	100.37	99.76	99.72	100.34
V	430	340	260	300	250	310	330
Cr	35	79	230	130	180	56	32
Co	51	46	46	48	52	48	41
Ni	58	57	160	91	140	68	80
Cu	240	120	53	150	90	120	85
Zn	120	150	89	130	110	120	210
Rb	7	12	41	40	8	2	14
Sr	140	200	210	140	190	85	260
Y	33	26	15	24	10	27	47
Zr	96	75	52	74	45	87	200
Nb	7	5	3	5	0	7	13
Ba	150	150	190	130	110	80	290
La	25	14	12	19	12	21	44
Yb	3.7	1.9	1.6	2.3	1.5	2.8	4.5

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